TESIS DOCTORAL

Transporte de sedimentos y restauración geomorfológica en la zona minera del Parque Natural del Alto Tajo (Guadalajara, España)

Sediment transport and geomorphic restoration in the mining area of the Alto Tajo Natural Park (Guadalajara, Spain)

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UNIVERSIDAD COMPLUTENSE DE MADRID

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MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

Ignacio Zapico Alonso

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José Francisco Martín Duque
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MEMORIA PARA LA OBTENCIÓN DEL TÍTULO DE DOCTOR

TRANSPORTE DE SEDIMENTOS Y RESTAURACIÓN GEOMORFOLÓGICA EN LA ZONA MINERA DEL PARQUE NATURAL DEL ALTO TAJO (GUADALAJARA, ESPAÑA)

SEDIMENT TRANSPORT AND GEOMORPHIC RESTORATION IN THE MINING AREA OF THE ALTO TAJO NATURAL PARK (GUADALAJARA, SPAIN)

Memoria de tesis doctoral presentada por Ignacio Zapico Alonso

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Madrid, marzo 2017

A mis padres, Luis y Elena

y a mis sobrinas, Sara y María

"…Just remember, there´s no such thing as a smooth mountain. If you want to make it to the top, then, there are sharp ridges that have to be stepped over…"

A brand new ending (Prince EA, 2016)

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Índice

Resumen

La minería genera importantes afecciones sobre el medio ambiente, sobre todo porque sus escorrentías suelen contener altas concentraciones de sedimentos. La contaminación asociada puede ser química o física, siendo los drenajes ácidos los más estudiados. Sin embargo, la contaminación física debida a escorrentías mineras ha recibido menos atención. Cuando la minería coexiste con otras fuentes de sedimentos, es preciso adquirir una amplia comprensión del conjunto de procesos de erosión y de transporte de sedimentos.

Se supone que todos estos impactos de raíz hidrológica y erosivo-sedimentaria deberían evitarse con buenas prácticas de restauración minera. No obstante, son numerosos los trabajos que demuestran los fallos recurrentes del método más ampliamente usado: sistemas talud-berma, o terrazas. Y por ello ha surgido la restauración geomorfológica, basada en diseñar y construir geoformas naturales, estables y funcionales, organizadas en cuencas hidrográficas.

En este contexto surge esta tesis, para tratar de aportar nuevo conocimiento sobre los problemas descritos. En investigaciones previas se identificó que las zonas mineras del entorno del Parque Natural del Alto Tajo (PNAT), eran la principal fuente de sedimentos terrígenos finos a la red fluvial, seguida de las cárcavas naturales. Sin embargo, aún son varias las preguntas sin respuesta, las cuales han motivado esta tesis: (i) se conoce poco sobre el mecanismo de transporte de sedimento de las cárcavas naturales, donde la carga de fondo es el proceso dominante; (ii) cuál es el efecto de las escorrentías procedentes del conjunto de las zonas mineras sobre la concentración de sólidos en suspensión (CSS) de los ríos que las reciben; (iii) la restauración geomorfológica puede ser

una solución eficiente para la problemática de esta zona, aunque hay una falta de evidencias cuantitativas sobre su viabilidad y éxito. Cada una de estas preguntas ha supuesto un bloque temático de mi investigación, llevada a cabo durante cinco años (2011-2016), con el título: *Transporte de sedimentos y restauración geomorfológica en la zona minera del Parque Natural del Alto Tajo (Guadalajara, España)*.

La carga de fondo ha sido estudiada en la principal cárcava del municipio de Poveda de La Sierra. Los objetivos fueron: (i) aportar datos continuos de flujo y textura de la carga de fondo en un sistema natural aún sin estudiar: un canal natural efímero, con alta pendiente, de arenas y gravas; (ii) relacionar los valores de carga de fondo con los cambios topográficos y de textura en el canal. El estudio se ha llevado a cabo con muestreadores tipo Reid, topografías de alta resolución medidas con Láser Escáner, fotogrametría moderna (Structure from Motion, SfM) y una vídeo-cámara automática. Los valores máximos de carga de fondo y textura (D_{90}) registrados oscilaron entre 0.2-9.6 kg s^{-1} m^{-1} y 1.81-49.4 mm respectivamente. Se ha identificado un patrón estacional en la morfología del canal, que a su vez afecta a la carga de fondo. En otoño, el canal muestra una incisión, y su textura es más gruesa, produciendo flujos de carga de fondo de mayor magnitud y texturas más rugosas. En invierno y primavera ocurre lo contrario, el canal se rellena de arena, mostrando texturas menos gruesas, que a su vez derivan en eventos de carga de fondo con flujos de menor energía y texturas más finas. Los eventos de verano son de transición. Esta alta variabilidad se debe al aporte de arenas desde las paredes de la cárcava y a la evolución de las barras en el canal.

La evaluación del impacto minero sobre la CSS de los ríos de la zona tuvo los siguientes objetivos: (i) definir la línea base de ese parámetro para el arroyo Tajuelo y el río Tajo; (ii) evaluar si esa línea base se veía afectada por las escorrentías de zonas mineras. Para ello se ha usado la metodología BACI (Before-After-Impact-Control), basada en tomar muestras simultáneas en los ríos aguas arriba (línea base) y aguas abajo (ya con las escorrentías mineras). El máximo valor de CSS aguas arriba de las minas fue de 24 g l^{-1}, mientras que su valor simultáneo aguas abajo era 391 g l^{-1}, un orden de magnitud mayor. El valor de aguas arriba, línea base, es 1000 veces mayor que el usado por la Unión Europea hasta 2015, 25 mg l^{-1}, para garantizar la calidad de las aguas salmonícolas. Las conclusiones fueron: (i) hay un impacto de las escorrentías procedentes de zonas mineras exentas de medidas de control sobre el régimen de CSS de los ríos estudiados; (ii) los 25 mg l^{-1} usados como referencia de calidad de las aguas no es realista. Sin embargo, concluimos que BACI sí lo es; (iii) se ha definido una línea base de CSS para los ríos de la zona minera del Alto Tajo.

La restauración geomorfológica de la mina el Machorro, a escala de cuenca hidrográfica, se ha diseñado y construido siguiendo la metodología GeoFluv-Natural Regrade, teniendo como objetivos: (i) confirmar la viabilidad de esta solución para esta zona; (ii) evaluar su estabilidad, monitorizando su respuesta hidrológica y erosivo-sedimentaria. Estos procesos de diseño, construcción y monitorización constituyen una contribución relevante en sí mismos, dado el escaso número de ejemplos equivalentes a nivel mundial. La monitorización se llevó a cabo durante tres años usando herramientas topográficas de alta precisión y una estación para la medición de escorrentía y CSS. El valor más

reciente de tasa de producción de sedimentos (2015-2016) fue de 18.4 Mg ha^{-1} $año^{-1}$. La literatura científica y distintas normativas internacionales corroboran que ese valor es asumible, y demuestra estabilidad para una zona minera restaurada. Aunque tanto en la construcción como en la monitorización hubo numerosos problemas y contingencias, se puede concluir que: (i) la restauración geomorfológica de la mina Machorro ha sido un éxito en términos de estabilidad; (ii) son necesarias futuras investigaciones para evaluar si la estabilidad actual perdura en el largo plazo.

Finalmente, integrando estas contribuciones parciales, se propone un modelo de restauración, control y manejo de la escorrentía, y la erosión-sedimentación para las minas activas del Alto Tajo: (i) adaptar restauraciones geomorfológicas GeoFluv-Natural Regrade al interior de las minas; (ii) usar el conocimiento adquirido sobre la línea base de CSS para regular los valores asumibles de escorrentía o vertido para ese parámetro; (iii) utilizar el conocimiento adquirido en el estudio sobre el transporte de sedimentos como carga de fondo para desarrollar futuras investigaciones sobre el movimiento de arenas y gravas tanto en el interior de las minas como en la red fluvial del Alto Tajo afectada por sedimentación.

Palabras clave: transporte de sedimentos, sólidos en suspensión, carga de fondo, restauración geomorfológica, Parque Natural del Alto Tajo, minería.

Abstract

Mining is a human activity with high associated environmental impacts. Runoff from mining areas is commonly contaminated and has high sediment loads. Water quality impact associated with sediment discharged from mines has not received the consideration it deserves. When mining coexists with other natural sediment sources, a broad understanding of erosion and sediment transport processes is needed.

Mining reclamation is supposed to decrease impacts of hydrologic and erosion-sedimentation origin. Nonetheless, failures have been common in the usual reclamation approach used worldwide because the resultant landforms are not functionally stable in the long-term. Alternatively, a new approach called geomorphic reclamation has arisen as a possible solution. This method is based on designs that replicate "natural", stable and functional, landforms and landscapes, organized in catchments.

This thesis has been carried out in this framework, trying to find the best possible knowledge related with the aforementioned problems, where mined sites were identified as the main small sized terrigenous sediment sources of the fluvial system, followed by gullies (natural origin). However, many questions remained unanswered and some of them motivated my research: (i) little is known about the sediment transport dynamics of the gullies of this area, where sand and gravel bedload is the main transport mechanism; (ii) the effect of runoff from mining areas on suspended sediment concentration (SSC) in the fluvial systems has not been generalized; (iii) geomorphic reclamation can be a reliable solution to be applied in this mining areas, but evidence of its implementation and monitoring

are needed. Hence, each one of these questions constitutes a topic in this thesis, undertaken during five years (2011-2016), entitled: *Sediment transport and geomorphic restoration in the mining area of the Alto Tajo Natural Park (Guadalajara, Spain)*.

Bedload transport has been studied in the Poveda gully. The aims were: (i) providing continuous bedload observations of flux and texture on a fluvial system that has not been reported hitherto: an undisturbed steep ephemeral gravelly sand channel; and (ii) relating bedload flux and texture to riverbed texture and topographic changes in the channel. Monitoring has been undertaken by using Reid-type slot samplers[1], together with high resolution topographies of the channel, surveyed with Terrestrial Laser Scanner (TLS), Structure from Motion (SfM), and an automatic video camera. The maximum bedload flux and texture (D_{90}) recorded varied in the range 0.2-9.6 kg s^{-1} m^{-1} and 1.8-49 mm respectively. In addition, a seasonal pattern in channel bed morphology and texture affecting bedload has been identified. In autumn the channel is incised, its texture is coarser and higher bedload fluxes with coarser bedload are produced. In contrast, spring and winter are associated with sand filling the channel, resulting in reduced bedload fluxes, and a decrease in bedload texture. Summer has transitional events. The evaluation of mining impact on SSC was undertaken with the aims of: (i) defining the SSC baseline for the Tajuelo stream and for the Tajo River; (ii) evaluating if there is an SSC impact associated with runoff from mining areas. A "Before-After Control-Impact" (BACI) approach was used to define a 2-year SSC baseline at stations situated upstream of the mining area of both rivers,

[1] A summary and analysis of the main technologies and instruments used during the thesis can be found in Appendix 3 (*Apéndice 3* in Spanish).

and compared with those downstream. The highest recorded SSC upstream of the mines was 24 g l^{-1} whereas the highest simultaneous downstream value was 391 g l^{-1}, more than one order of magnitude higher. Additionally, the former value is 1000 times more than the unrealistic average concentration of 25 mg l^{-1}, used by the European Union until 2015 to guarantee the quality of salmonid waters. The conclusions of this study are: (i) there is an effect of derelict mining areas without sediment control structures on SSC dynamics on the Tajuelo and the Tajo rivers; (ii) the all-European 25 mg l^{-1} value, suggested as standard, is not a consistent reference to quantify SSC impacts whereas, BACI is a reliable method to quantify impacts; and (iii) an SSC baseline has been defined for these two rivers.

A geomorphically-based mining reclamation at the El Machorro mine has been designed and built at a watershed scale following the GeoFluv-Natural Regrade method, with the aims of: (i) confirming its feasibility to this physiographic setting; and (ii) evaluating the reclaimed landform stability by monitoring the hydrologic and erosive-sedimentary response. El Machorro geomorphic reclamation (the design and building processes) and its monitoring are a contribution in themselves, because there are few examples worldwide. The hydrological and erosive-sedimentary response of the geomorphic reclamation was monitored during three years by using high-resolution topographic tools and a runoff-SSC station. The most recent sediment yield for the 2015-2016 period was 18.4 Mg ha^{-1} $year^{-1}$. This value is more than acceptable, considering the scientific literature and some mining regulations. Although there were drawbacks during the process of the geomorphic reclamation and subsequent monitoring, we conclude that: (i) the El Machorro geomorphic restoration has been a success in terms of stability

and (ii) further research is needed to evaluate if the present stability remains in the long term.

Stitching these studies and their outcomes, a model for reclaiming, controlling and managing the runoff, erosion and sedimentation of the active kaolin mines of the Alto Tajo is proposed: (i) adapting GeoFluv-Natural Regrade geomorphic reclamation solutions for the interior of the mines (ii) using the gathered knowledge on SSC baseline for the Tajuelo and Tajo waterways for regulating allowed SSC; and (iii) taking advantage of the knowledge gained in the bedload study to further research the movement of sand and granules both within the mines and in the affected channels and main stem of the Alto Tajo.

keywords: sediment transport, suspended sediment, bedload, geomorphic restoration, Alto Tajo Natural Park, mining.

Estructura de la memoria

La memoria de la tesis cuenta con un primer bloque, en el que se encuentra **el resumen** de la tesis, tanto en español como en inglés.

Posteriormente, en el **capítulo 1** de introducción, se exponen los antecedentes tanto globales como locales que han enmarcado y motivado esta tesis, desarrollada en la zona minera del Alto Tajo. Dada la temática de la tesis y las características de la zona de estudio, se ha analizado el estado de conocimiento relativo al transporte de sedimentos en áreas fuentes tales como zonas mineras y cárcavas. También se hace un repaso de los diferentes métodos para la cuantificación del impacto minero sobre el régimen de transporte de sedimentos de los ríos que reciben escorrentías mineras. Además, se lleva a cabo una breve descripción de la evolución de la práctica de la restauración geomorfológica en espacios mineros, y finalmente se exponen los objetivos e hipótesis de la investigación.

Los siguientes tres capítulos suponen el eje central de la tesis. Cada uno de ellos tiene una estructura independiente, pero similar, en forma de artículo científico (introducción, área de estudio, métodos, resultados, discusión y conclusiones) y están escritos íntegramente en inglés. El motivo por el que se ha adoptado esa estructura es que los tres trabajos se encuentran en distintas fases de publicación como artículos científicos. Sin embargo, a pesar de contar con esa estructura de *paper*, no se ha incluido el listado de referencias bibliográficas al final de cada uno, sino que éstas se han incorporado a un apartado general de bibliografía de la tesis para tratar de adoptar un formato 'global' más próximo a una tesis 'clásica'. El **capítulo 2** aborda el transporte de carga de fondo de una de las principales fuentes naturales de sedimentos de la zona, la cárcava de Poveda. En este capítulo se reproduce íntegramente el manuscrito que se enviará próximamente a la revista *Earth Surface Processess and Landforms*. El **capítulo 3** por un lado, describe el establecimiento de líneas base (baseline) de concentración de sedimentos en suspensión en ausencia de afección por actividades extractiva, para dos cursos fluviales (Tajuelo y Tajo) en distintos estados de régimen fluvial (estiaje y crecida), así como el efecto que las escorrentías mineras tienen sobre la modificación de esos valores, una vez que éstas han llegado a los cursos fluviales referidos. En este capítulo se reproduce íntegramente el artículo aceptado el 20 de agosto de 2016 en la revista *Land Degradation & Development*. El **capítulo 4** expone un proceso completo de restauración geomorfológica en la mina el Machorro, incluyendo su diseño, construcción, y la la monitorización de su respuesta hidrológica y erosiva. Aquí se reproduce íntegramente el manuscrito que será enviado a la revista *Ecological Engineering*.

Posteriormente se incluyen los capítulos de discusión general en castellano (**capítulo 5**) y conclusiones en inglés (**capítulo 6**) de la tesis. En el primero se hace una síntesis y análisis crítico de los principales métodos y técnicas utilizados en la tesis. También se hace una evaluación general de todos los resultados obtenido. Finalmente se termina con una propuesta o modelo para contribuir a garantizar una minería sostenible en el Alto Tajo, a modo de síntesis sobre el estado del conocimiento en este ámbito, tras años de investigación en el mismo. Las conclusiones, por su parte, tratan de reflejar la verdadera esencia de la contribución al conocimiento que constituye esta tesis.

Tras estos capítulos se encuentran los apartados de **referencias bibliográficas**, **listas de figuras** y **tablas y una lista de acrónimos**.

Finalmente se incluyen dos tipos y grupos de **Anexos**: el primer grupo está constituido por dos vídeos en formato electrónico, que forman parte del capítulo 2 (**Anexos 1 y 2**) y que se encuentran en el CD adjunto. El segundo grupo está formado por dos anexos en formato papel, que son: una versión en inglés del análisis crítico del conjunto de tecnología e instrumentos usados durante la tesis desarrollado en el capítulo de discusión (**Anexo 3);** y un resumen de enlaces a materiales disponibles en Internet, sobre trabajos complementarios a esta tesis, realizados en el mismo periodo, y con conexión clara con los contenidos de la misma (**Anexo 4)**.

Además de los Anexos 1 y 2, el **CD adjunto** también incluye una copia de la memoria de la tesis en formato pdf, que permite, entre otras cosas, facilitar el acceso a las diferentes direcciones de internet que se citan en el documento.

Capítulo 1

Introducción

Introducción

1.1. Impacto de la minería sobre la dinámica hidrológica fluvial

La minería, actividad imprescindible para nuestro bienestar, genera importantes afecciones sobre el medio ambiente. Su influencia en el proceso de Cambio Global en el que nos encontramos actualmente inmersos, es significativa. Sirva como ejemplo que el movimiento de tierras producido por la minería a nivel mundial se situaba, ya en 1994, por encima de las 30 Gt al año, valores comparables e incluso superiores a los de los agentes geológicos naturales referidos a esa misma fecha (Hooke, 1994). En esta misma línea argumental, un estudio reciente (Mudd & Boger, 2013) ha demostrado que la industria minera es el mayor productor de residuos sólidos. En concreto, en ese estudio se reporta que la producción anual (para 2011) de residuos mineros es de 7.1 miles de millones de colas (*tailings*, relaves) y de 55.9 miles de millones de toneladas de residuos de escombreras. Todo ello equivale a una media anual de nueve toneladas de residuos mineros por persona y por año. La superficie terrestre libre de hielos modificada por la actividad del hombre, con influencia sobre los procesos de erosión-sedimentación (afectando, como mínimo, a la cubierta vegetal), es actualmente superior al 50%, y un 0,3% del total de la superficie terrestre corresponde a actividades extractivas (Hooke *et al.*, 2012). En realidad, ese valor no es elevado (en comparación con un 13 % de la superficie terrestre dedicado a agricultura, o un 23 % dedicado a zonas de pastos (Hooke *et al.*, 2012), si bien este impacto suele llevar asociado un cambio profundo del paisaje, debido principalmente a una drástica transformación de la topografía. A modo de ejemplo, un reciente estudio sobre la zona minera de la cuenca del río Sil (León, España) ilustra muy bien cómo, durante 50 años, la minería del carbón, de pizarra y las graveras han alterado significativamente amplias superficies de la topografía de esa comarca (Redondo-Vega *et al.*, 2017). En la actualidad, un porcentaje no despreciable del nuevo paisaje de esa comarca consiste en grandes huecos mineros y escombreras asociadas. Todo ello ha generado un deterioro evidente de los ecosistemas, en una zona protegida por varias figuras, tales como Red Natura o Reserva de la Biosfera.

Si bien se puede pensar que estos cambios radicales del terreno y ecosistemas sólo están restringidos al 0,3% de la superficie terrestre planetaria libre de hielos, los impactos ambientales de la minería también pueden extenderse a decenas de kilómetros aguas debajo de las superficies mineras, referido únicamente de impacto hidrológico. El más importante a nivel mundial es el asociado a la minería metálica, donde la inestabilidad física y química de muchos de sus pasivos (como las balsas de 'colas', *tailings* o 'relaves'), pero también de explotaciones activas sin control suficiente, pueden terminar contaminando los terrenos y cursos fluviales aledaños, con todos los riesgos ambientales asociados que ello conlleva (Macklin *et al.*, 2006; Oyarzun *et al.*, 2010; Oyarzun *et al.*, 2011; Kossoff *et al.*, 2014; Martín-Duque *et al.*, 2015).

Relacionado con lo anterior, aunque no exista presencia de metales también la minería puede ocasionar episodios de contaminación de naturaleza física, debido a la emisión de sedimentos detríticos, cuya raíz es la erosión hídrica favorecida por prácticas de explotación y restauración inadecuadas o ineficientes. Esta erosión, por una parte, limita el desarrollo del suelo y la vegetación (Soulard *et al.*, 2015; Tarolli & Sofia, 2016) y por tanto de ecosistemas funcionales en la propia zona afectada por la minería. Por otro lado, también produce emisiones elevadas de agua y sedimentos, las cuales generan desequilibrios en la dinámica natural de los cauces situados aguas abajo de las zonas mineras, ocasionando la ya mencionada contaminación física (Martín-Moreno *et al.*, 2016; McIntyre *et al.*, 2016). El resultado es un impacto ecológico significativo tanto en los espacios mineros como en zonas adyacentes que están conectadas hidrológicamente.

1.2. Transporte fluvial de sedimentos y su posible modificación por minería

El transporte de sedimentos en un río es el proceso por el que el agua es capaz de movilizar sedimento como consecuencia de su circulación por el canal que lo encauza. En este flujo, los materiales pueden ser transportados, principalmente (Richards, 1982; Summerfield, 1991):

(i) En disolución, que como su propio nombre indica que los materiales transportados están disueltos y dispersados a través de todo el flujo. Este tipo de transporte suele tener poco efecto en la forma que adoptan los canales aluviales, que es reflejo de la disposición de la carga sólida.

(ii) Como carga sólida (Fig. 1.1). Ésta, a su vez, tiene dos tipos dominantes:

a) carga de fondo (*bedload*): hace referencia a todo el material que viaja teniendo algún contacto con el fondo (lecho) del canal y que es, por tanto, arrastrado. Sin embargo, no todas las partículas son movilizadas en el fondo de los canales de la misma manera: algunas partículas viajan rodando por el canal (*rolling)*, otras reptando (*sliding*) y el resto por saltación (*saltation*). Y dependiendo de las condiciones del flujo de agua, existen cambios en la modalidad de transporte para un mismo tamaño. Así, por ejemplo, determinadas partículas que viajan como saltación podrán pasar a viajar en suspensión en regímenes de mayor energía.

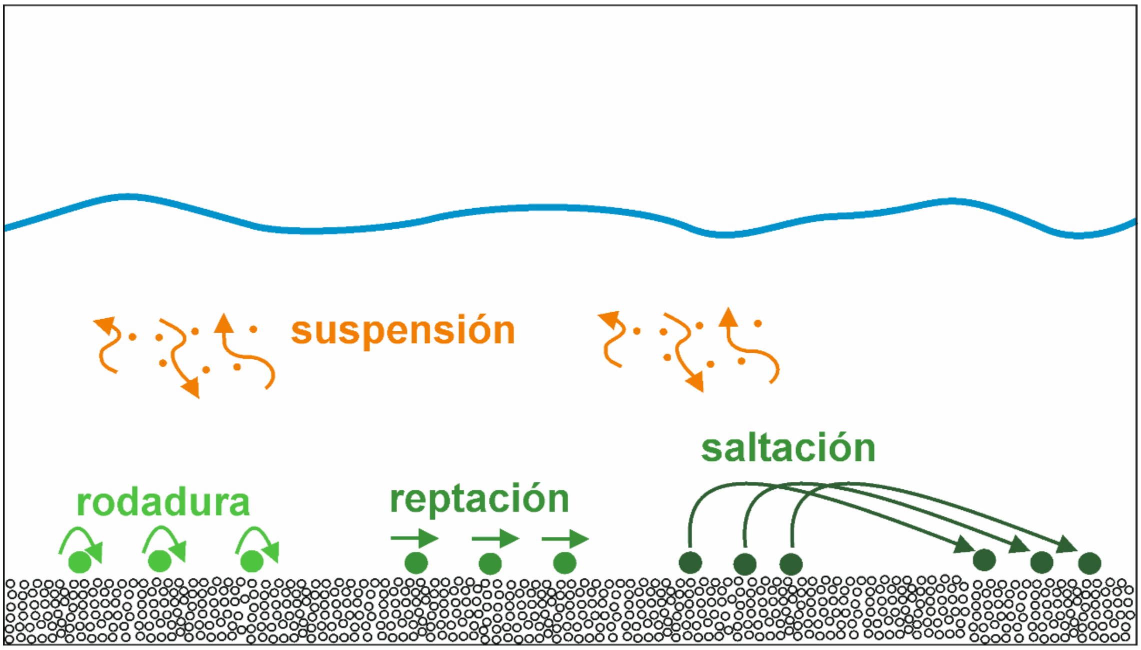

Figura 1.1. Representación esquemática de los modos de transporte de sedimento de carga sólida en aguas corrientes. Redibujado a partir de Summerfield (1991).

b) en suspensión (*suspended load*): es el material que se mantiene suspendido en el flujo de agua debido a la existencia de remolinos y corrientes turbulentas en el fluido agua. Esta modalidad se divide en dos tipos: 'carga de lavado' (*wash load*) que es aquel material que viaja suspendido forma continua en el flujo de agua, incluso a caudales bajos y que depende de los aportes de sedimento al río; y carga de fondo movilizada en suspensión (*suspended bed material load*) que son materiales presentes en el fondo del canal pero que sólo se ponen en suspensión ante flujos de transporte con energía elevada. El total de materiales en suspensión se refiere como Concentración de Sólidos en Suspensión, CSS (*Suspended Sediment Concentration, SSC*) y se suele medir y expresar en mg l^{-1} o g l^{-1}.

Aunque uno de los síntomas más evidentes de erosión hídrica en zonas mineras, es la detección de altos valores de sedimento en los cursos fluviales situados aguas abajo (Messina & Biggs, 2016), hay que tener en cuenta que: (i) la erosión hídrica de la superficie terrestre es un proceso natural, al igual que el posterior transporte del sedimento por los cursos fluviales (Anderson & Anderson, 2015); y (ii) hay paisajes que en ausencia de minería también están sujetos a altos valores de erosión, y de transporte de sedimentos en sus ríos; ya sea como consecuencia de otras actividades humanas, como agricultura o urbanización (Wotling & Bouvier, 2002; Ramos *et al.*, 2015), o de forma natural, por la presencia de cárcavas o *badlands* (Nadal-Romero et al., 2008; López-Tarazón et al., 2009; Ionita et al., 2015). Por esta razón, antes de evaluar si existe un impacto de la minería sobre el régimen de sedimentos en un sistema fluvial es necesario estudiar sus valores en ausencia de escorrentías de zonas mineras (línea base, o *baseline*), así como todas las fuentes que vierten sus sedimentos a los ríos en los contextos mineros objeto de estudio.

Las cárcavas y *badlands* como fuentes naturales de sedimento de las redes fluviales han sido objeto de numerosos estudios. La mayoría de ellos se ha centrado en cuantificar su producción total de sedimentos (Della Seta *et al.*, 2007; Martín-Moreno *et al.*, 2014) y otros también han abordado la cuantificación de las tasas de actuación de los distintos procesos que concurren en estos paisajes (Nadal-Romero & Regüés, 2010; Lucía *et al.*, 2013; Taguas *et al.*, 2015; Ranga *et al.*, 2016; Vanmaercke *et al.*,2016).

En lo que se refiere a las zonas mineras como fuentes de sedimentos del sistema fluvial, los enfoques tradicionales y más extendidos para estudiar la producción de sedimentos son el uso de modelos de erosión, como RUSLE o WEPP, o los denominados Modelos de Evolución del Paisaje *(Landscape Evolution Models,* LEM), como SIBERIA o CESAR (West & Wali, 1999; Evans, 2000; Hancock *et al.*, 2008; Taguas *et al.*, 2010; Trabucchi *et al.*, 2012; Hancock *et al.*, 2016a, 2016b) y también medidas directas en parcelas de erosión (Merino-Martín *et al.*, 2012, Lowry *et al.*, 2014; Martín-Moreno *et al.*, 2016). Una revisión extensa sobre la literatura referida a la estimación de tasas de erosión en zonas mineras, tanto por métodos directos como indirectos, se puede encontrar en Martín-Moreno (2013). Sin embargo, son muy pocos los estudios que han tratado de cuantificar la respuesta erosiva e hidrológica de paisajes mineros a nivel de cuenca y con medidas directas (Martín-Moreno, 2013; Bugosh & Epp, 2014). Este tipo de investigaciones son necesarias, dado que: (i) las medidas directas en parcelas de erosión no representan la complejidad real de una zona minera restaurada o sin restaurar, que se extiende en magnitudes casi siempre superiores a decenas de hectáreas; (ii) los métodos indirectos, salvo que estén muy bien calibrados, siempre tienen una cierta incertidumbre.

Una forma de cuantificar el impacto de las escorrentías mineras sobre el régimen de sedimentos de los cursos fluviales es el cálculo de la producción de sedimentos *(sediment yields)* en los ríos. Algunos de los estudios desarrollados en esa línea se centran en evaluar cómo varía la producción de sedimentos del río afectado, a lo largo de los años, y a medida que la actividad minera evoluciona (Walling & Fang, 2003), aunque no permiten conocer de forma precisa lo que corresponde a cada fuente de sedimentos involucrada. En otros estudios calculan la producción de sedimentos de un río simultáneamente antes y después de recibir escorrentías mineras (Pentz & Kostaschuk, 1999; Chalov, 2014). Ambos enfoques son muy útiles para cuantificar el impacto general de la actividad minera una vez que éste se ha producido.

Otra forma de cuantificar este tipo de impacto físico alternativa a la producción de sedimentos es la llevada a cabo mediante la determinación de CSS. De esta forma es más fácil establecer lo que podríamos traducir como “valores desencadenantes” *(trigger values),* superados los cuales se considera que se está produciendo contaminación física, tal y como hicieron Evans *et al.* (2004) en la cuenca del Ngarradj, Australia. Es decir, establecer valores umbrales de CSS permite que se puedan usar para evaluar episodios de contaminación en el momento en que se producen ya sea mediante muestras manuales (más fácil, barato y práctico de llevar a cabo por parte de las autoridades) o sensores.

En la actualidad, la mayoría de las minas activas, prácticamente a nivel global, y al menos en países con una cierta exigencia legal al respecto, suelen tener controlado el impacto hidrológico de sus escorrentías mediante distintos sistemas para el control de la escorrentía, la erosión y la sedimentación. En minas similares a las del Alto Tajo (minería de caolín en laderas), estos sistemas consisten en balsas que retienen el sedimento y la escorrentía producidos como consecuencia de la actividad extractiva. Con estas estructuras se impide que la gran mayoría de la producción de escorrentía y sedimentos salga del interior de las minas. Del mismo modo, las zonas mineras donde la actividad ha cesado se debería de controlar este impacto, gracias a la restauración de las mismas o a la adopción de otro tipo de medidas de control de la escorrentía, la erosión y la sedimentación (artículo 167, sobre suspensión y abandono de labores, de la Ley de Minas española de 1973; BOE, 1973). En todo caso, éste es un tema complejo, pues depende de la historia de la actividad extractiva en cuestión y de su desarrollo en el tiempo (en relación a las distintas normativas que le fueran aplicables). Sin embargo, incluso en presencia de medidas correctoras, son numerosos los estudios que han documentado los continuos fallos de las restauraciones mineras convencionales, como por ejemplo las basadas en la construcción de terrazas con perfiles rectilíneos (Haigh, 2000; Sawatsky, 2000; Bugosh, 2009).

1.3. Restauración Geomorfológica

Los métodos de restauración de zonas mineras basados en construir laderas de pendiente uniforme están actualmente en “revisión” respecto a su estabilidad a largo plazo y a su integración ambiental. En este contexto y en contraposición surge una nueva disciplina llamada Restauración Geomorfológica (*Geomorphic Reclamation*, OSMRE, 2016) que se basa en proponer diseños que repliquen las formas naturales del terreno (Simon-Coinçon *et al.,* 2003; Schor & Gray, 2007; Martín Duque *et al.,* 2010). Este nuevo enfoque se puede definir como una aplicación moderna de la ciencia geomorfológica, el cual está dirigido al diseño y reconstrucción de geoformas similares a las “naturales” en lugares transformados por la minería en superficie, también denominada “a cielo abierto”, adaptable a explotaciones abandonadas, inactivas, activas y futuras. Aunque pueda parecer que el principal objetivo de replicar geoformas “naturales” en espacios afectados por actividades mineras tiene un propósito “estético”, el fin último, sin embargo, es favorecer la estabilidad dinámica del terreno, restituyendo ecosistemas y paisajes funcionales, dinámicos y autosostenibles. En la actualidad, una de las herramientas más avanzadas para poder llevar a cabo la Restauración Geomorfológica es el método GeoFluv™, implementado en el *software* Natural Regrade (Bugosh, 2000, 2003).

1.4. La zona minera del Alto Tajo

El Parque Natural del Alto Tajo se encuentra situado entre las provincias de Guadalajara y Cuenca (Fig. 1.2) y su excepcional valor ambiental motivó su declaración con tal figura de protección en el año 2000 (DOCM, 2000).

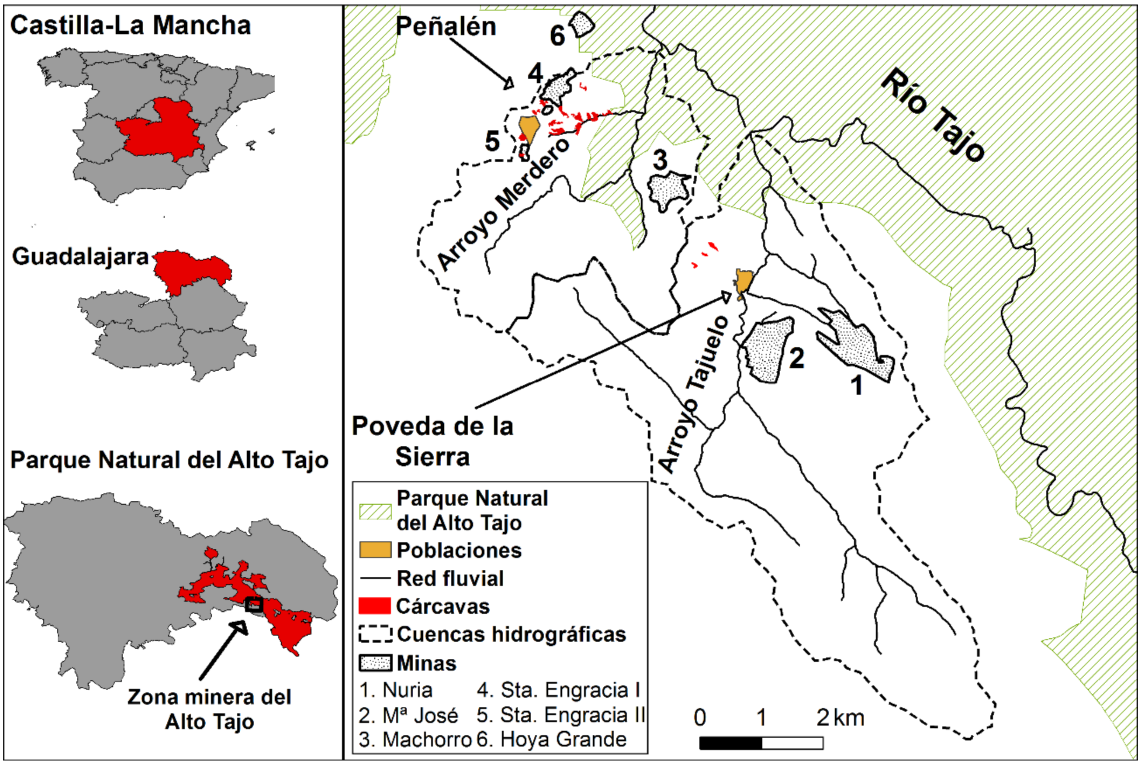

Figura 1.2. Situación de la zona minera del Parque Natural del Alto Tajo.

De todas las características que posee el Parque y que motivaron su reconocimiento como espacio natural protegido, la más importante es la alta calidad de sus aguas (Fig. 1.3), que favorece el desarrollo de especies faunísticas y vegetales de alto valor ecológico ligadas al medio acuático (Carcavilla *et al.*, 2011). A su vez, para entender bien la importancia de los ecosistemas fluviales en este entorno, baste citar que el río Tajo cuenta, dentro del Parque, con más de 100 km de hoces y cañones, labrados por los cursos fluviales en las parameras calcáreas del Sistema Ibérico.

Figura 1.3. Vista del cañón del Tajo, en las proximidades del Puente de San Pedro. Reproducida de Carcavilla et al. (2011). Nótese la claridad del agua.

Este entorno natural está dando lugar a una creciente actividad económica en el ámbito del turismo rural y del ocio al aire libre, siendo estas actividades las de mayor potencial de desarrollo en la zona (DOCM, 1999). Sin embargo, en la actualidad una de las principales actividades económicas es la minería de caolín, la cual se desarrolla en las cuencas de dos de los afluentes del río Tajo: el Tajuelo y el Merdero (Fig. 1.2) y que genera el 13.5% de los puestos de trabajo de la zona (DOCM, 1999).

Como minería a cielo abierto con entidad mecanizada moderna, la actividad en estas minas comenzó en 1965 (apertura de la mina María José). De estas minas se extrae, actualmente, el 60% del caolín nacional (Lázaro Sánchez, com. Pers.).

Este mineral arcilloso se utiliza en industrias muy diversas, si bien el material procedente del Alto Tajo tiene mayoritariamente un uso cerámico.

Las minas de caolín de este entorno están fuera del Parque Natural (porque, de hecho, el espacio protegido es posterior a los derechos y concesiones de explotación), pero se sitúan en las mismas cuencas hidrográficas, de modo que sus escorrentías (agua y sedimentos) están potencialmente conectadas a los arroyos Tajuelo y Merdero y en última instancia al río Tajo (Fig. 1.3 y 1.4). Esta zona también cuenta con fuentes naturales de sedimentos, como son varias cárcavas de arenas y gravas (Fig. 1.2).

Figura 1.4. Vista de las desembocaduras del arroyo Tajuelo (izquierda) y del arroyo Merdero (derecha) al río Tajo durante un evento de precipitación y la posterior crecida acaecida en estos cauces (9.11.2012). Las flechas indican la dirección del flujo.

1.5. Punto de partida de la investigación

En este contexto de coexistencia espacial de recursos minerales y ecológico-paisajísticos verdaderamente muy valiosos, se vienen desarrollando investigaciones desde 2007. Los objetivos son entender la problemática ambiental de raíz hidrológica, y cuantificar los procesos, naturales y antrópicos, involucrados en ese contexto. El objetivo de todas estas iniciativas es determinar bajo qué condiciones y circunstancias puede ser viable la extracción de caolín (un mineral importante tanto para la sociedad como para los habitantes de la zona), en un entorno tan significativo como es un Parque Natural.

Las investigaciones que se han llevado a cabo hasta la fecha en relación con el impacto de origen hidrológico, de erosión de suelos, y de emisión de sedimentos asociados a la minería del entorno del Alto Tajo (Martín-Moreno, 2013; Martín-Moreno *et al.*, 2014, 2016) han puesto de manifiesto lo siguiente:

(i) Las fuentes de sedimentos más importantes a la red fluvial del Alto Tajo (Fig. 1.2), en las cuencas vertientes al tramo del río Tajo desde el entorno de Peralejos de las Truchas hasta el puente de Peñalén tienen un doble origen: (i) cárcavas naturales; (ii) espacios afectados por minería de superficie (origen antrópico).

(ii) La tasa de producción de sedimentos desde las cárcavas (Fig. 1.5) ha sido cuantificada en 114 Mg ha^{-1} $año^{-1}$. Este valor ha sido estimado a partir de medidas directas (sedimentación en diques de corrección hidrológica) para la cárcava de Ribagorda, situada aguas arriba de la zona minera del Alto Tajo (Martín-Moreno *et al.*, 2014).

(iii) Respecto a las fuentes de origen antrópico, minas, el estudio doctoral (Martín-Moreno, 2013) demostró que existen dos tipologías de las mismas respecto a la conexión hidrológica sedimentaria entre minas y red fluvial: (i) aquéllas que carecen de medidas para el control de la escorrentía, la erosión, y la emisión de sedimentos (como la mina Santa Engracia; Fig. 1.4); (ii) aquéllas que sí incluyen medidas para ese control, como las minas María José y El Machorro; Fig. 1.2. En un caso intermedio se situaría la mina Nuria, que por un lado carece de medidas de restauración (salvo retazos antiguos de terrazas) y por otro dispone de un dique de corrección hidrológica que retiene los flujos de escorrentía procedentes de una parte muy importante de la superficie minera.

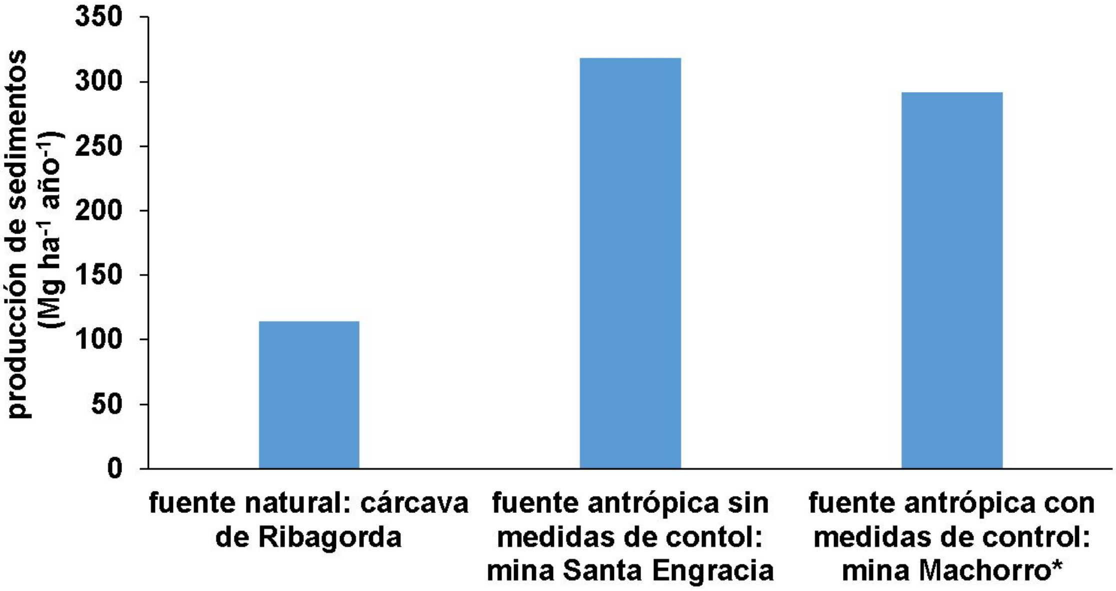

*Figura 1.5. Comparación de las tasas de producción de sedimentos calculadas para las fuentes de sedimentos más importantes de la zona minera del Parque Natural del Alto Tajo (a partir de Martín-Moreno, 2013), *El sedimento de esta mina es retenido por un sistema de balsas de control de la escorrentía y la sedimentación, y por tanto no existe conectividad con la red fluvial, tal y como ocurre con los otros dos casos.*

Respecto a las primeras, en el caso de la mina Santa Engracia (Fig. 1.5) se estimó que sus escombreras exteriores, sin ningún tipo de control hidrológico o erosivo-sedimentario, producían una tasa de 318 Mg ha^{-1} año^{-1}. Respecto a las segundas, el principal mecanismo de control hidrológico y erosivo-sedimentario consiste en una serie de balsas de sedimentación y decantación (Fig. 1.6), las cuales laminan posibles crecidas, al tiempo que retienen la carga de fondo, y favorecen la decantación de sólidos en suspensión.

Figure 1.6. Vista aérea oblicua de la Mina María José, en donde es posible identificar el sistema de balsas (rojo) para el control de la escorrentía y la sedimentación y su sistema de interconexión (líneas azules), tanto en el interior del hueco minero como desde las escombreras exteriores. Foto Paisajes Españoles.

Aprovechando los datos de limpieza de las balsas de decantación de alguna de estas minas activas (Fig. 1.7), se cuantificó una tasa de erosión interior en la mina, es decir, que no se vierte al río (al quedar retenido en balsas de sedimentación), de 292 Mg ha^{-1} año^{-1} (Fig. 1.5).

Aun así, estos sistemas de control no pueden retener toda la escorrentía generada en ciertos eventos extremos, ni garantizar que no se emita una cierta cantidad de sólidos en suspensión, por rebose de dichas balsas, durante esos eventos. Esta circunstancia, lejos de constituir un “problema ambiental”, constituye, a nuestro entender, la constatación de una realidad “dinámica”, que es la siguiente: los espacios ocupados por explotaciones mineras deberían poder “entregar” a los cursos fluviales situados aguas abajo, volúmenes de escorrentía y concentraciones de sedimentos en suspensión equivalentes a los de la línea base (para ese mismo espacio). De hecho, de no hacerlo, es decir, de no emitir escorrentía y sedimentos en valores similares a los anteriores a la actividad minera, estarían causando un impacto ambiental, al detraer los caudales y sedimentos que las redes fluviales recibían de manera "natural".

Figure 1.7. Vista del proceso de limpieza de una de las balsas del sistema de retención de sedimentos en la mina Machorro.

(iv) Los sistemas de restauración del terreno que se han venido utilizando en las minas de caolín del Alto Tajo (escombreras troncopiramidales, con laderas escalonadas o en terrazas) si bien muestran una amplia variabilidad en su comportamiento (desde totalmente inestables, como en Santa Engracia, hasta relativamente estables, como en María José, El Machorro o las más antiguas de la mina Nuria), presentan dudas respecto a su estabilidad "en el largo plazo". Por ello, en este mismo contexto minero del Alto Tajo se han desarrollado nuevos métodos y aproximaciones de restauración, con base geomorfológica, cuyo principal resultado fue el siguiente (Martín Moreno *et al.*, 2016): la construcción de laderas cóncavas cubiertas con tierra vegetal, y sin ningún tipo de semillado, ofrecía el mejor resultado, combinando una baja tasa de producción de sedimentos 16-20 Mg ha^{-1} $año^{-1}$ y un alto grado de biodiversidad vegetal (el espacio fue colonizado por 14 especies de forma espontánea).

Aparte de los trabajos citados anteriormente, existe otro estudio que aborda la problemática del impacto de la actividad minera sobre el régimen de transporte de sedimentos del sistema fluvial del Alto Tajo en este entorno minero. Se trata del *Estudio y Plan de Seguimiento limnológico del Parque Natural del Alto Tajo* (Bravo *et al.*, 2004). En dicho estudio se ofrecen datos del muestreo, durante 2003-2004, de la CSS de varias estaciones situadas en algunos cauces próximos a las explotaciones mineras. El esquema planteado para la toma de muestras en esas estaciones seguía un patrón que incluía localizaciones situadas tanto aguas arriba como aguas abajo, para tratar de diferenciar los valores de los tramos de los ríos con ausencia de influencia minera de aquéllos que sí tuvieran esa influencia. Sin embargo, a la hora de discutir los resultados no comparan las muestras siguiendo ese mismo esquema, sino que los comparan con el valor exigido hasta 2015 por la Unión Europea, es decir 25 mg l^{-1} (Directive 2006/44/EC).

Como resultado final de esta comparación concluyen que hay un impacto sobre la CSS asociado a las zonas mineras, dado que en varios de los muestreos se supera el valor umbral de 25 mg l^{-1}. No obstante las estaciones que no reciben escorrentías de las zonas mineras también superan algunas veces dicho valor. A pesar de este probable impacto en la CSS, en el informe se concluye que la calidad del río Tajuelo parece no verse comprometida por este incremento en la CSS. Este estudio está limitado por varias razones, algunas de las cuales están señaladas por los propios autores:

(i) El estudio anual sólo se limita a 13 muestras en cada punto, número insuficiente para representar la complejidad de un río. Además, tampoco se dice en qué condiciones del río se recogieron las muestras.

(ii) El uso de 25 mg l^{-1} como valor umbral de contaminación para aguas salmonícolas. Sin embargo, la ley dice que este valor se refiere a concentraciones medias y que puede tener excepciones debido a características geográficas particulares o por circunstancias meteorológicas excepcionales, tales como inundaciones. En ese contexto, en nuestra opinión, lo que la propia normativa describe como excepcionalidad es una característica natural intrínseca de cada río. La CSS en particular y el transporte de sedimentos en general son valores de alta variabilidad entre diferentes ríos y dentro del mismo río a lo largo del año (flujo base, crecida, recesión, estacionalidad, tramo concreto del río que se trate…). Todo ello suele llevar a una incorrecta interpretación de la directiva. Prueba de ello es que los autores de este informe, aun cuando tenían datos de CSS de los ríos de estaciones que no recibían escorrentías mineras, no los han usado para comparar con las muestras que sí tenían escorrentías mineras, sino que han usado los 25 mg l^{-1}.

En ese mismo informe, para solventar estos problemas, se señala que para un conocimiento adecuado del impacto de la actividad minera sobre los ríos, sería clave instalar un sistema de medición continuo de recogida de muestras, que es el que se ha realizado en el marco de esta tesis.

1.6. Retos para seguir avanzando en la comprensión de la problemática hidrológica relacionada con la minería del Alto Tajo

A pesar del conocimiento adquirido hasta la fecha sobre la problemática hidrológica relacionada con la minería en el entorno del Parque Natural del Alto Tajo, varias son aún las preguntas que quedan sin respuesta, y que han motivado el desarrollo de esta tesis:

(i) Se desconocen, por completo, los mecanismos de transporte de sedimentos de las cárcavas de la zona, ya que los trabajos previos se centraron en cuantificar tasas anuales de producción y además sólo en cárcavas de arena. En este sentido tiene especial interés el conocimiento de la dinámica del transporte de sedimentos desde estos sistemas, tal y como se ha realizado en otro trabajo desarrollado en cárcavas similares (Lucía *et al.*, 2013), donde se demostró que en este tipo de cárcavas arenosas entre el 70 y el 99% del sedimento se moviliza como carga de fondo.

    En especial conviene conocer la dinámica relativa al transporte de sedimentos de la cárcava de arenas y gravas de Poveda, la más importante en la cuenca del río Tajuelo, y la única de toda la zona minera que reúne las condiciones necesarias para instalar el tipo de instrumentos adecuados a las preguntas de investigación sin respuesta.

(ii) En el apartado anterior se ha visto como las minas abandonadas de Santa Engracia, con medidas de restauración muy ineficientes, suponen la principal fuente de sedimentos en esta zona, con valores de producción de sedimentos (318 Mg ha^{-1} $año^{-1}$) que son incluso superiores a los de una cárcava natural de gran tamaño, como es la cárcava de Ribagorda (114 Mg ha^{-1} $año^{-1}$). No obstante, no se conoce su influencia sobre el régimen de transporte de sedimentos de los sistemas fluviales una vez que éstos han incorporado sus escorrentías.

Las tasas de erosión referidas en el párrafo anterior, se refieren al total de sedimentos. Sin embargo, el contexto para el estudio del impacto minero es el siguiente: la emisión de sedimentos desde las cárcavas puede considerarse “natural” o, como mínimo, “incorporada” por los sistemas fluviales de esta comarca durante siglos; a su vez, la emisión de sedimentos desde entornos como el de Santa Engracia constituyen una “anomalía” en el funcionamiento minero, ya que las minas activas de este entorno, ni pueden ni realizan vertidos directos de sedimentos a las redes fluviales. Desde éstas, únicamente es posible emitir escorrentías por reboses de balsas de control de la erosión y la sedimentación, cuyos sedimentos se transportan, únicamente, como sólidos en suspensión.

En definitiva, para conocer el impacto real de las escorrentías de origen minero sobre el régimen de transporte de sedimentos de los ríos que las reciben (Tajuelo, Merdero y Tajo), es necesario establecer una línea base *(baseline)* que represente la complejidad natural del régimen de transporte de sedimentos en suspensión de los ríos que reciben escorrentías de las minas. Éstos son los únicos que se podrían ver afectados teniendo en cuenta la regulación actual, que no permite a las minas verter carga de fondo. Posteriormente éstos tienen que ser comparados con datos medidos aguas debajo de las zonas mineras, para cuantificar local y verazmente el impacto de la actividad minera.

Este tipo de estudios, que deben estar basados en la toma de muestras aguas arriba y abajo de las zonas mineras, para el entorno del Parque Natural del Alto Tajo sólo se puede establecer para el arroyo Tajuelo y el río Tajo. Ello es así porque la cuenca del arroyo Merdero está totalmente modificada, y carece de tramos fluviales que representen las condiciones naturales del arroyo sin impacto de la minería (Martín-Moreno, 2013).

(iii) La introducción de principios geomorfológicos en las prácticas de restauración, como fue la construcción de laderas cóncavas (Martín-Moreno *et al.*, 2013), dejó entrever que este tipo de enfoques pueden ser más exitosos que los tradicionales, basados en terrazas. Esto es así porque pueden restituir una funcionalidad hidrológica y erosiva - sedimentaria en los espacios restaurados, pero manteniendo, al mismo tiempo, una estabilidad en el largo plazo. Sin embargo, falta el reto de estudiar una restauración geomorfológica a escala de cuenca hidrográfica, durante un espacio de varios años, y comprobar si este enfoque puede ser una solución viable para la minería en el Alto Tajo.

Para cada una de estas preguntas se ha definido un estudio (Fig. 1.8). Aunque los tres están relacionados y tienen como objetivo avanzar en el conocimiento de la temática de transporte de sedimentos en la zona minera del Alto Tajo, y en conocer si la restauración geomorfológica restituye dinámicas equilibradas hidrológicas y erosivo-sedimentarias, en la memoria se han abordado por separado, constituyendo tres capítulos independientes. Al tratarse de temas específicos, y localizados en diferentes partes de la zona minera (cárcava, tramos fluviales o una mina), cada uno de ellos seguirá una estructura de artículo científico: introducción, área de estudio, métodos, resultados discusión y conclusiones.

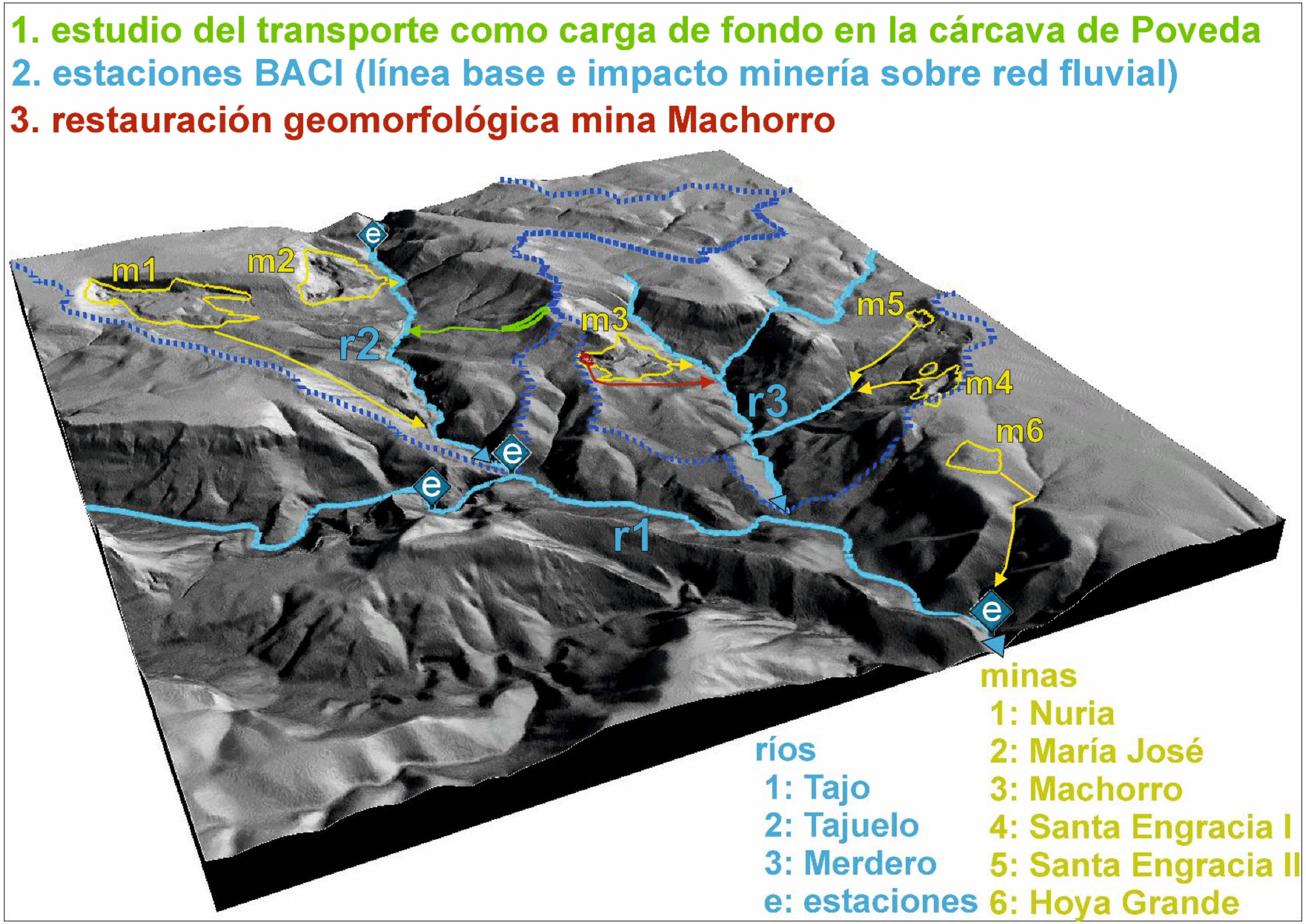

Figura 1.8. Contexto de los estudios desarrollados en esta la tesis, en la zona minera del Alto Tajo.

1.7. Objetivos de la tesis

Para cada uno de los tres retos señalados en el apartado anterior se han definido los siguientes objetivos:

Dinámica del transporte de carga de fondo de un canal efímero de arenas y gravas de una cárcava natural (capítulo 2):

1. Conocer los flujos y textura de la carga de fondo de un canal efímero y natural de arenas y gravas, lo cual no se ha estudiado con anterioridad en la naturaleza (sólo en flumes).

2. Establecer relaciones entre los parámetros que explican el transporte de carga de fondo con los cambios topográficos en el mismo canal.

Impacto de la actividad minera sobre el régimen de transporte de sedimentos de los ríos que reciben sus escorrentías (capítulo 3):

3. Definir la línea base *(baseline)* de la Concentración de Sólidos en Suspensión (CSS) en el arroyo Tajuelo y el tramo del río Tajo antes de recibir escorrentías de la zona minera.

4. Evaluar si existe alguna influencia de las escorrentías mineras sobre las aguas de las redes fluviales adyacentes, en relación a la CSS.

Restauración geomorfológica a escala de cuenca hidrográfica y monitorización de su respuesta hidrológica y erosiva (capítulo 4):

5. Plantear, diseñar y construir una Restauración Geomorfológica a escala de cuenca hidrográfica usando la metodología GeoFluv^{TM} y el *software* Natural Regrade.

6. Monitorizar la respuesta hidrológica y erosiva de dicha restauración, para evaluar su comportamiento.

1.8. Hipótesis

A continuación, se exponen las principales hipótesis de partida para cada uno de los tres temas de estudio:

Dinámica del transporte de carga de fondo de un canal efímero de arenas y gravas de una cárcava natural (capítulo 2):

- Que tanto el canal, como el transporte de carga de fondo, van a tener una gran variabilidad estacional a lo largo del año en cuanto a la textura, al flujo de la carga de fondo y en cuanto a las formas del canal.

- Que el transporte de gravas está muy condicionado por las formas aparecidas en el lecho, tales como barras y parches, así como por el aporte de arenas desde las paredes de la cárcava.

Impacto de la actividad minera sobre el régimen de transporte de sedimentos de los ríos que reciben sus escorrentías (Capítulo 3):

- Que la CSS de los cursos fluviales estudiados va a incrementar sus valores al recibir escorrentías de zonas mineras.

- Que la forma de evaluar el impacto de la minería sobre la CSS de los cursos fluviales de este entorno usando un único valor estándar (como son los 25 mg l^{-1}), es insuficiente para representar la variabilidad natural de ese parámetro en la red de drenaje de la zona.

Restauración geomorfológica a escala de cuenca hidrográfica y monitorización de su respuesta hidrológica y erosiva (capítulo 4):

- Que la restauración ecológica con principios geomorfológicos de una superficie afectada por minería, mejorará la estabilidad de las formas del terreno.

-

Capítulo 2

The sand/gravel ratio: seasonal effects on bedload flux and texture in the Poveda Gully, Spain

El presente capítulo reproduce íntegramente el artículo que será enviado próximamente a la revista *Earth Surface Processes and Landforms*

The sand/gravel ratio: seasonal effects on bedload flux and texture in the Poveda Gully, Spain

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Abstract

We report on bedload transport in a natural, steep, sand-gravel ephemeral channel draining the small Poveda Gully watershed in the mining area of the Alto Tajo Natural Park, Spain. First-ever continuous bedload flux and texture monitoring in a transitional sand-gravel environment was undertaken by two independent Reid-type slot samplers. Morphological changes in the channel upstream of the samplers were simultaneously quantified after events by TLS (Terrestrial Laser Scanning) and SfM (Structure from Motion) technologies. We identified a seasonal pattern in channel bed morphology and texture (morpho-texture) affecting bedload: in autumn the channel is incised, its texture is coarser and higher bedload fluxes with coarser bedload are produced. In contrast, spring and winter are associated with sand filling the channel, resulting in reduced bedload fluxes, and decrease in bedload texture (mainly sand). Summer has transitional events. Video camera recording during events allowed identification of dramatic changes in bedload flux and texture due to the appearance and erosion of bars. We propose a conceptual model tying sand input, bed morpho-texture, bedload flux and bedload texture.

Keywords: bedload flux, bedload size, gravel-sand, steep ephemeral channel, seasonal channel morphology.

2.1. Introduction

Bedload transport is the main process by which fluvial landscapes form and evolve, also determining river activity. Its understanding is required for river management and planning of fluvial infrastructures such as dams and bridges (Batalla & Vericat, 2011). Sand-gravel bed systems have been studied mostly in flumes (Wilcock & McArdell, 1993; Wilcock & McArdell, 1997) showing how grains of a specific size in a mixed-size bed are entrained over a range of shear stresses and that only part of the bed material is entrained, the rest remaining immobile, thereby defining partial bedload transport. The range of shear stresses and the proportion of active grains vary depending on the initial texture and its variation through a flow event. Also, the range of sizes in a state of partial transport increases with flow strength, and full mobilization of each all grains is achieved only at a shear stress when the proportion of grains of a given size in bedload is equal to their proportion in the bed surface (Wilcock & McArdell, 1993). In addition, it has been shown that sand plays an important role in gravel mobilization; the latter is rapidly increased when sand represents 14-27% of the bed (Wilcock *et al.*, 2001). Flume studies can reproduce bedload fluxes comparable to those in nature, however field studies are required to quantify bedload processes accurately in large events with higher shear stresses (Kuhnle *et al.*, 2014).

Bedload measurements in nature are demanding due to high temporal and spatial variability (Gomez, 1984) and the interaction of different sizes of bed material (Parker, 2008). They are also expensive, time consuming and dangerous in some settings (Gray *et al*., 2010). Several devices for continuous direct measurement of bedload transport at a fixed location have been used such as the continuous belt slot system (Leopold & Emmett, 1977), the channel-wide vortex slot (Milhous, 1973), the ultrasonic sensor system developed in Rio Cordon (D'Agostino & Lenzi, 1999) and the Reid-type recording slot sampler (Reid *et al.*, 1980). Surrogate monitoring technologies such as Acoustic Doppler Current Profilers – ADCPs (Gaeuman & Jacobson, 2006), geophones (Mizuyama e*t al.*, 2010; Rickenmann & Fritschi, 2010), hydrophones (Belleudy *et al.*, 2010), and seismic sensors (Burtin *et al.*, 2011) are nowadays available. Although these surrogate methods are capable of continuously monitoring bedload, they are to a large extent experimental (with exceptions; e.g., Rickenmann *et al.*, 2014), requiring the collection of physical samples for calibration. The most widespread and accurate method for continuous bedload monitoring is the Reid-type recording slot sampler, successfully used in permanent and ephemeral gravel bed rivers worldwide (e.g., García *et al.*, 2000; Laronne *et al.*, 2003; Vericat & Batalla, 2010).

Studies on bedload in sand-gravel stream have been done in ephemeral streams (Lucía *et al.*, 2013) with the Reid sampler while other methods were used in perennial streams (Kleinhans & Ten Brinke, 2001; Claude *et al.*, 2012, Kuhnle *et al.*, 2014). These studies provided information on bed and bedload dynamics in sand-gravel rivers.

Studies of morphological changes in gravel bed rivers have been undertaken using High Resolution Topographies (HRTs), among others for estimating sediment budgets (Lane *et al.*, 1994; Brasington *et al.*, 2000; Lane *et al.*, 2003; Williams *et al.*, 2013). However, it is difficult to relate bedload transport parameters at the event scale to changes in channel morphology because it requires a complete topographic survey of the channel reach in question both prior to and following a bedload transporting flow event (Kasprak *et al.*, 2015). For this reason, studies of topography and bedload have been undertaken mainly in flumes (Kasprak *et al.*, 2015), only6 few in the field (Williams *et al.*, 2015). Hitherto information is lacking on means by which bedload flux and texture are interrelated with channel morphology and texture (morpho-texture), because prior field studies have not included observations on morphological changes *during* bedload transporting events, on the detailed morphotexuture prior to and after events, nor on the simultaneous capture of continuous bedload data (Lucía *et al.*, 2013).

We report on a study carried out the ephemeral sand-gravel channel of Poveda Gully located close to the Alto Tajo Natural Park in east-central Spain (Guadalajara province), the first-ever in this kind of environment. The park is a protected area with a presumed environmental problem caused by high yields of sediment from kaolin mines and from sand gullies, both located in the geologic

Utrillas Formation (Martín-Moreno *et al.*, 2014; Zapico *et al.*, 2017). Hence it is essential to understand bedload dynamics from natural gullies, such as the Poveda Gully, to compare it with bedload resources in the mined areas and to evaluate their relative impact on the Alto Tajo River (Zapico *et al.*, 2017).

The aims of this study are: (i) providing continuous bedload observations on a fluvial system that has not been reported yet: an undisturbed steep ephemeral gravelly sand channel by continuously monitoring bedload flux and texture; (ii) relating bedload flux and texture to riverbed texture and (iii) analyzing topographic changes in the upstream feeder reach and its interaction with bedload flux and texture.

2.2. Study Area

The Poveda Gully is located in East-Central Spain (Fig. 2.1) close to the Alto Tajo Natural Park. This landscape is characterized by plateaus and mesas capped by Cretaceous carbonate rocks (limestones and dolostones) underlain by sandy sediments, in which the Tajo River has incised a canyon system longer than 100 km and up to 400 m in depth (Carcavilla *et al.*, 2011). The sandy sediments are 100 m thick (Arenas de Utrillas Formation) into which several gullies have incised, the largest of which is the Ribagorda Gully (Martín-Moreno *et al.*, 2014). These sands contain thin layers of gravels, as well as kaolinite, the latter exploited in several mines in the vicinity of the Natural Park (Olmo & Álvaro, 1989).

The most common soils are calcaric cabisols, mollic leptosols and rendzic leptosols on top of the mesas, and carbonate colluvia with calcaric cambisols on the slopes (IUSS Working Group WRB, 2007). The vegetation is representative of Mediterranean continental environments, with communities dominated by

Spanish juniper (*Juniperus thurifera)*, pine (*Pinus nigra* subsp. *salzmanii*) and gall oak (*Quercus faginea*) (MARM, 1997–2006).

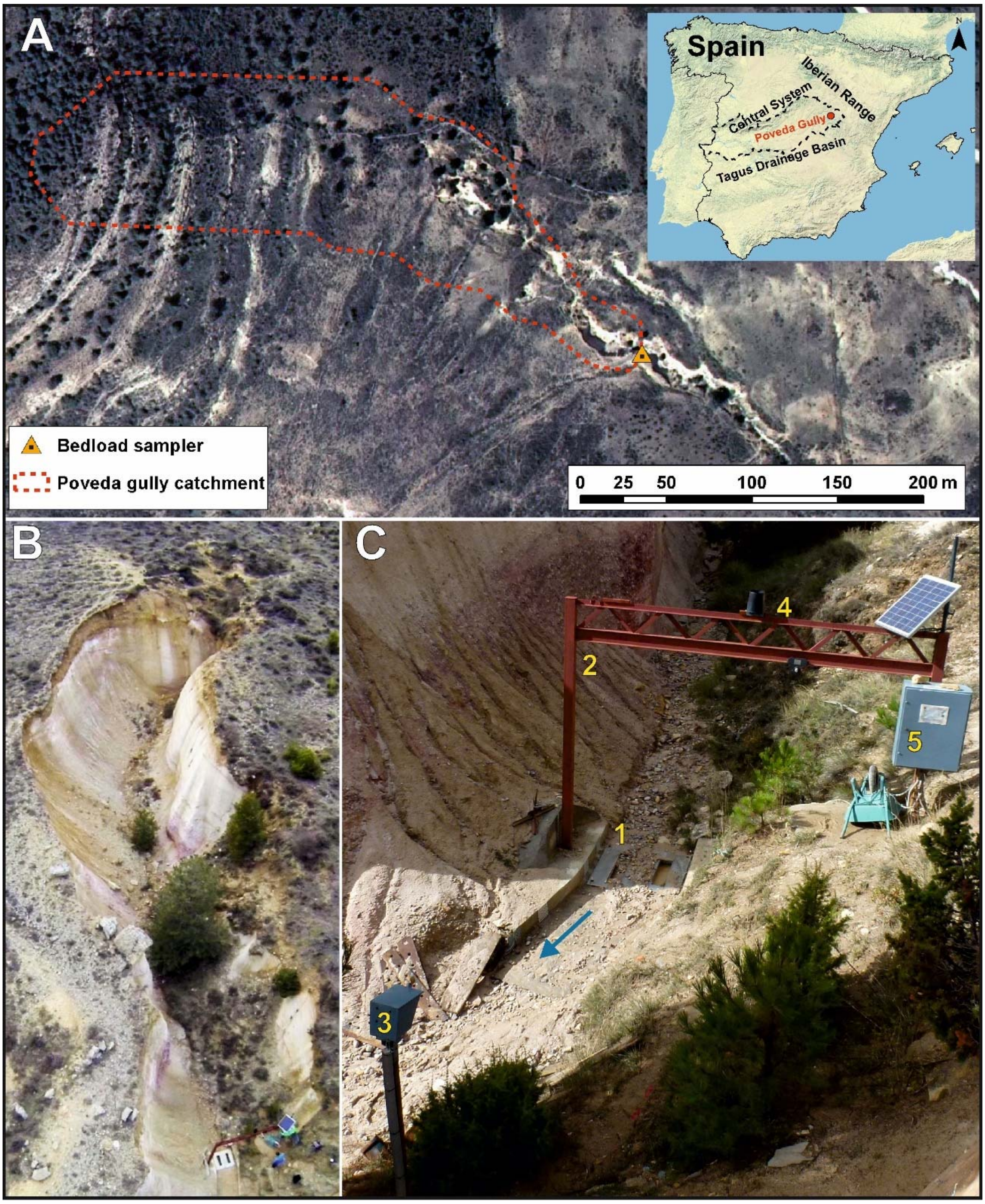

Figure 2.1. A) Location of the Poveda Gully; B) oblique aerial photograph; C) monitoring equipment. 1: two Reid slot bedload samplers; 2: crane to lift the samplers; 3: video camera; 4: rain gauge; 5: solar panel, batteries, datalogger and telemetry.

The climate is temperate Mediterranean with dry and mild summers (Csb, according to Köppen 1918) and with a continental influence. Mean annual precipitation is 783 mm and mean annual temperature is 10°C (AEMET, 2013). Seasonally, this area is characterized by long and cold winters with snow being common, and short and dry summers. Spring and fall are usually wet. The rainfall erosivity factor, R (equivalent to the R factor of RUSLE), is estimated to be about 800 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988).

The Poveda Gully is located in the Tajuelo catchment, one of the tributaries of the Tajo River. This gully (0.24 ha gullied; 2.8 ha the area of the entire catchment) and other few very minor gullied areas in its vicinity (Fig. 2.1) represent 0.01% of the Tajuelo catchment. The longitudinal slope of the Poveda gully channel is 9º and its width at the monitoring site is 1.15 m. The vertical gravelly sand walls have slopes of 50º and 31º in the right and left banks respectively. Their height is approximately 5 m. The channel bed has a variable proportion of sand and gravel where D_{50} and D_{90} respectively vary in the range 15-40 mm and 30-80 mm.

The Grain Size Distributions (GSDs) of the Poveda channel bed before monitoring was initiated are shown in Fig. 2.2. The D_{50} of the shallow subsurface and subsurface are similar in sandy gravel and gravelly bars (between 0.85 and 3.5 mm), whereas the median of the thalweg is much coarser (7.5 mm in the shallow subsurface).

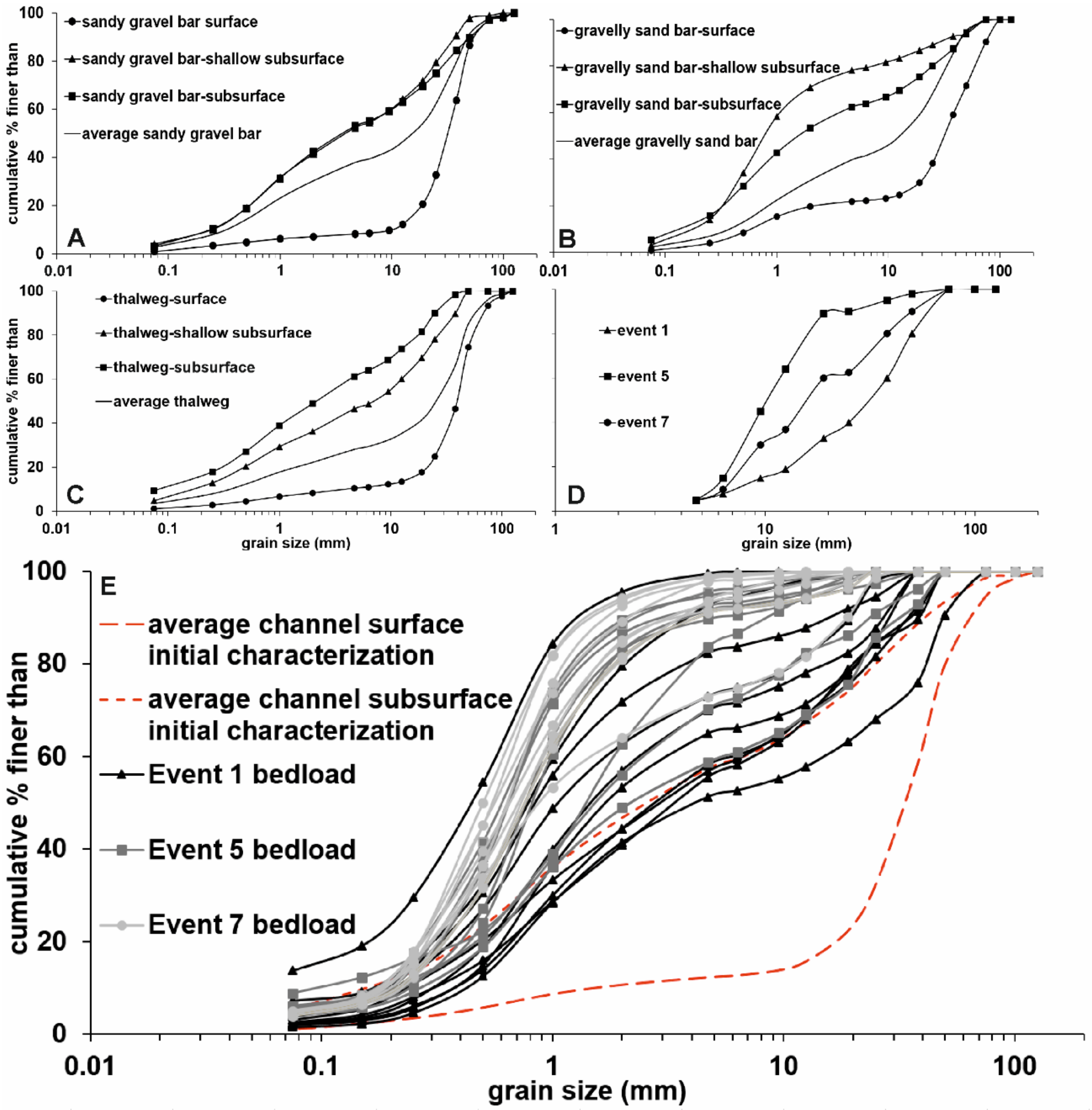

Figure 2.2. Sediment textures in the Poveda Gully. A, B, C: bedmaterial characterization in the different units undertaken before bedload monitoring ensued; D: channel bed after events 1, 5 and 7, the roughness-based texture from ToPCAT for granule (< 5 mm) grain sizes; E: bedload samples (right sampler) after events 1, 5 and 7.

2.3. Methods

Bed characterization

Bed forms and texture of the channel were undertaken on April 19, 2013 prior to initiation of monitoring. To avoid modifying the studied channel upstream of the monitoring site, the sampling was undertaken further downstream on the following bed patches: (i) thalweg area, (ii) gravelly sand bar, (iii) sand gravel bar,

(iv) gravel bar. These morpho-textural units were sub-sampled in three 'layers': (i) painted surface, (ii) shallow to D_{max} subsurface and (iii) subsurface. Sediment bars were sampled in their entirety. Samples were sufficiently large with respect to the D_{max} to ensure 1% of error (as per Church *et al.*, 1987). Samples were dried and sieved with grain size parameters calculated using Gradistat (Blott & Pye, 2001).

Topographic surveys after each bedload-transporting event

High resolution topographies of the channel were surveyed after each bedload event to evaluate interrelationships between bedload texture and bed changes upstream of the samplers. We used two methods: (i) Terrestrial Laser Scanning (TLS) after two among the seven registered events and (ii) automatic photogrammetry (Structure from Motion – SfM; see Westoby *et al.*, 2012) after four of the events. One additional bed topography was surveyed using both methods for inter-comparison and determination of their relative accuracy. Topographic data after two minor events are unavailable.

TLS was undertaken with a Leica MS60 multiStation. This instrument is also a total station, thus allowing measurement of check points as well as control points with 1 mm precision. The MS60 automatically unified the scanned point clouds to remove shadows. Table 2.1 shows details of the scans.

Two sets of photographs were taken by SfM from 1.5 m and 10 m heights using a DMC TZ20 Panasonic and a Xiaoyi Action cameras. The number of photos differed; however, all sets had a minimal 80% overlap. Twelve fixed targets were placed along the channel as check or control points. Their coordinates were measured with the MS60. Photos were processed with Agisoft PhotoScan

(Agisoft LLC, 2016) to obtain a dense ultra-high quality point cloud and an orthophoto.

Table 2.1. Topographic data availability and accuracy obtained after each bedload transporting event.

event	method	nº photos or scan positions	point cloud density	RMSE check points: nº check points	RMSE check points: X,Y	RMSE check points: Z
		#	pts m^{-2}	#	m	
1	SfM	252	8,073,836	3	0.02	0.007
2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
3	LIDAR	2	184,195	n.d.	n.d.	n.d.
4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
5	SfM	27	997,152	3	0.02	0.002
6	SfM	121	2,539,025	3	0.02	0.004
6	LIDAR	4	220,601	n.d.	n.d.	n.d.
7	SfM	115	775,659	3	0.02	0.003
A	SfM	131	928,368	3	0.02	0.002
A	LIDAR	2	254,955	3	0.015	0.004

n.d. - no data; A – after the 7th event for comparison of SfM to LIDAR.

Before processing point clouds, each one was 'cleaned' to remove non-ground elements such as vegetation or noise using the LP360 Advanced edition software (Qcoherent, 2015). Once the topographies were processed, four analyses were performed to calculate:

(i) the volumetric difference between back to back topographies using the Cut/Fill LP360 tool. Referring to a constant analyzed channel bed area (6 m^2), we transformed the volume gained or lost between topographies towards an average value of difference in height. Errors were also calculated (Brasington *et al.*, 2000);

(ii) the relative relief for a specific part of the channel;

(iii) the roughness-based bed material grain size distribution (GSD) by calculating the Root Mean Square Height (RMSH) - the standard deviation of height in a specific detrended area - for which the slope has been removed (Hodge *et al.*, 2009a; Hodge *et al.*, 2009b; Brasington *et al.*, 2012; Rychkov *et al.*, 2012). Both roughness and GSD were calculated using ToPCAT (Brasington *et al.*, 2012; e.g. see Storz-Peretz *et al.*, 2015); and

(iv) the percent change in bedforms achieved by digitalizing the bedforms and the thalweg area using orthophoto and point clouds in ArcGIS Pro 1.3.1 (ESRI, 2016). For these analyses bed forms were sorted as gravel and sandy gravel bars and sand and gravelly sand.

Topographies were surveyed with several check points, independent positions measured with the MS60 but not used to geo-reference. The root-mean-square error (RMSE) of their location was used to determined accuracy. It was calculated with the LP360 control point tool following the American Society for Photogrammetry and Remote Sensing guidelines (ASPRS, 2014). The RMSE was determined only once for the TLS-based topographies, but every scan was undertaken using the same control points and following the same procedure. Table 2.1 shows accuracy results. The largest RMSE in height (RMSEZ) is 7 mm, smaller than the smallest average difference in height between topographies (12 mm). Therefore, the calculated differences in topography are reliable.

Bedload, water discharge and rainfall

Bedload discharge was automatically and continuously monitored during 24.10.2014 and 02.11.2015 by two independent, cross-sectionally aligned Reid type bedload slot samplers (Reid *et al.*, 1980). This method has previously been employed in gravel (Laronne & Reid, 1993), gravelly-sand (at the Jornada

Experimental Range, see Laronne *et al.*, 2003), sandy (Lucía *et al.*, 2013) as well as in clayey-gravel ephemeral channels (Liébault *et al.*, 2016). Our equipment and sampling methodology are identical to those used in the Barranca de los Pinos (Lucía *et al.*, 2013). Bedload trapped by the slots is at times stratified inside the two samplers, allowing the determination of the texture of bedload. Samplers were always full of water to ensure that all the changes in mass detected by the system were only due to entry of sediment.

The pressure sensors were locally calibrated following Lucía *et al*. (2013) using known weights ranging in mass between 0.2 and 40 and kg. The minimum mass detected by the sensors was 0.20 kg. The maximum cumulative mass during calibration was almost 900 kg, exceeding the total load accumulated during sampling.

Water stage was monitored at the study site by two calibrated vented pressure transducers located in each of the bedload slot samplers. Water density was assumed constant at 1043 kg m^{-3} based on few samples of suspended sediment. Channel average shear stress was calculated as (Du Boys, 1879):

$$\tau = \rho w \ d \ S \ g \qquad (1)$$

where τ is shear stress (kg m^{-1} s^{-2}), ρ_w water density (kg m^{-3}), *d* is water depth (m), S is bed slope (nondimensional) and g gravity (9.81 m s^{-2}). We realize that water surface slope and water depth varied in and across the reach immediately upstream of the slot samplers. The calculation of local shear stress based on (1) is merely made to demonstrate the large variations of local shear stress and the large cross sectional variations of bedload flux.

Rainfall was measured by two recording tipping-bucket rain gauges (Davis Rain Collector II) installed nearby.

The bedload equipment (Fig. 2.1) and methods were similar to those deployed in Barranca de los Pinos (Lucía *et al*, 2013), with changes as follows: (i) slot widths were set at 160 mm; each slot had two wings to avoid lateral entrance of bedload (Liébault *et al.*, 2016). The slot size was determined by monitoring painted gravel particle movement during the year preceding bedload measurements; the diameters of the largest mobile clast was 145 mm. The downstream dimension of the slots was much larger than anticipated hop lengths of saltating particles (Fathel *et al.*, 2015); (ii) a concrete wall was installed on the right bank of the sampler to avoid the entrance of sediment from the gully wall (Fig. 2.1); (iii) bedload samples were dried and sieved at 0.062, 0.25, 0.5, 2, 4.7, 6.3, 9.5, 19, 25, 38, 50, 75, 100 and 125 mm; (iv) the data logger (Campbell CR1000) was connected to a telemetering system, informing when an event occurred and the mass of sediment inside the samplers. This allowed emptying the samplers after every event, thereby avoiding the loss of any event; (v) to ensure appropriated representation of clasts for textural analysis, the sediment in the boxes was sampled from the top center instead of from the lateral window.

Finally, because these bedload samplers are recording type, the time during which a given layer of bedload sediment was deposited can be determined. The time during which each bedload sample was trapped was determined by the cumulative bedload mass assuming a constant density of the deposit as found elsewhere (Powell *et al.*, 2001). This timing allowed calculation of cumulative bedload mass (kg), bedload flux (kg s^{-1} m^{-1}), shear stress (kg m^{-1} s^{-2}) and bedload texture (mm). For ease of graphical representation of bedload flux we used hg m^{-1} s^{-2}.

Still and video photography

An M12 video camera (Mobotix) was installed with the view field 10 m upstream the monitoring site. It was triggered by the data logger when the pressure sensors detected water in the channel. The camera shot at a rate of 1 photograph/s during the entire period when water was detected in the channel. A light was also triggered at night-time. The images were converted to video using the Mobotix MX Control Center program. The video was synchronized with the pressure sensor data.

The camera allowed qualitative analysis how bedload entered into the slots, but also how the changes in bedload flux and texture related to changes in bed topography during Events 5 and 8.

2.4. Results

Flow events

As the Poveda Gully is an ephemeral channel, it is dry almost all of the year. During the annual monitoring period (24.10.2014 - 02.11.2015) altogether seven bedload generating flow events occurred (Table 2.2). Two short duration events (2 and 4) registered low cumulative bedload mass although they were preceded by considerable rainfall. Event 1 at a timing of the highest rainfall depth for the entire study period, also produced the largest bedload mass.

Table 2.2. Summary of the monitored bedload generating flow events in the Poveda Gully.

event	date	season	rainfall depth (duration) before event	rainfall depth (duration) during event	max bedload size[1] D_{90}	max bedload size[1] D_{50}	bedload mass in both samplers[2]	max local bedload flux[1]	max local shear stress[1]	max water depth[1]	event duration[3]
			mm (h)		mm	mm	kg	kg s^{-1} m^{-1}	kg m^{-1} s^{-2}	mm	min
1	03.11.2014	autumn	19.2 (7)	13.4 (4)	49.4	4.25	466	6.2	164	107	245
2	14.11.2014	autumn	10.8 (1)	9.2 (1.5)	1.81	0.63	50	0.5	37	24	85
3	30.01.2015	winter	6.2 (6)	23.8 (16.5)	1.87	0.77	132	0.2	30	19	985
4	26.04.2015	spring	15 (11)	4.2 (1)	3.23	0.99	42.5	0.2	43	28	52
5	11.06.2015	spring	4.4 (2)	2.4 (0.5)	32	2.2	314	9.6	120	78	25
6	21.08.2015	summer	3.0 (1)	8.2 (4.5)	7.90	1.11	164	2.3	83	54	235
7	02.11.2015	autumn	4.6 (1)	5.8 (2.5)	18.82	1.1	368	1.9	127	83	150

[1] Maximum values at both samplers.

[2] Total bedload mass inside both samplers.

[3] The beginning and the end of an event were defined by the beginning and of sediment entry into the samplers if not full, or until sampler efficiency dropped (Powell *et al.*, 2001).

Maximum registered water depth was 107 mm during Event 1, respectively 78 and 83 mm during Events 5 and 7. The highest fluxes of bedload were registered in Events 1 and 5. Although water depth was shallow in comparison to other channels where bedload was monitored, local shear stresses were high because the channel slope is very high (0.15). The maximum registered local shear stress was 164 kg m^{-1} s^{-2}. Event duration varied in the range 25 - 985 min; the two small bedload transporting Events 2, 4 lasted about 1 hr (Table 2.2).

Bedload flux

The total mass of accumulated bedload exceeded the sampler volume only during Event 7 (Table 2.2). Magnitudes of the topmost local bedload flux were high by all standards, up to 9.6 kg s^{-1} m^{-1}. Events 1, 5 and 7 occurred in autumn and spring, producing a gravelly sand texture and the largest masses of bedload. In contrast, Events 2, 3, 4 and 6 occurred in summer, spring and winter transporting a sandy gravel with lower bedload yields. Most of the sediment was trapped by the right sampler in all the events; in some events (2, 3, and 6) the accumulation of sediment inside the left sampler was insignificant.

These dramatic variations in bedload transport between events also occurred during each event. Fig. 2.3a shows the evolution of sedimentary parameters monitored in Event 5, one of the three events with high values of total accumulated bedload mass in both samplers. Note that the scales for all parameters vary between the left and right samplers. The single-peaked hydrograph is not repeated in the temporal variation of bedload flux, which considerably varies in both samplers. During the short 26 min duration of Event 5, bedload flux varied approximately between 0 and 10 kg s^{-1} m^{-1} in the right sampler and 0 and 1 kg s^{-1} m^{-1} in the left sampler. During merely 3 minutes (between minutes 2-5) bedload flux rose 5-fold and then decreased 5-fold although water depth continuously increased from 5 to 7 cm. A smaller rise and fall in bedload flux occurred somewhat earlier in the left sampler.

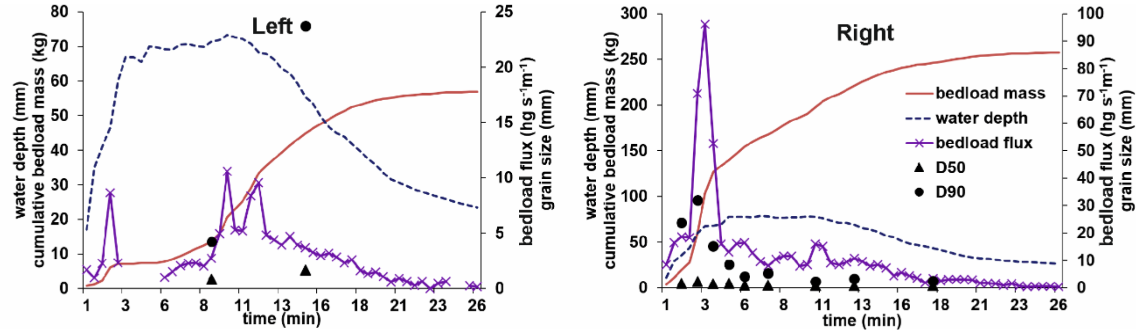

Figure 2.3a. Temporal variation of water depth, bedload flux, cumulative bedload mass, D_{50} and D_{90} during event 5. The unit of bedload flux is hectograms/sm for ease of illustration.

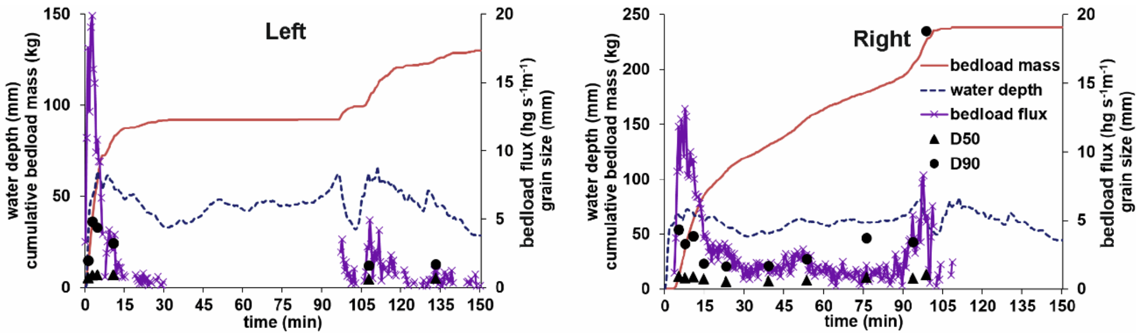

Figure 2.3b. Temporal variation of water depth, bedload flux, cumulative bedload mass, D_{50} and D_{90} during event 7. The unit of bedload flux is hectograms/sm for ease of illustration.

Similar high temporal variations in bedload flux seemingly unrelated to water depth also occurred during Event 7 (Fig. 2.3b). Here, large bedload fluxes were registered in both samplers during the initial 10 minutes, first in the left sampler (2 kg s^{-1} m^{-1}) and 5 min later in the right sampler (1.5 kg s^{-1} m^{-1}). Also, striking is the inactivity in the left sampler during minutes 30-100 and the opposite - the lack of bedload activity in the right sampler during the last 45 minutes while the left side of the channel became active even through water depth was similar throughout the entire width of the monitored channel.

These large changes in bedload flux are reproduced by depicting the variation of bedload flux with shear stress (Fig. 2.4). For instance, Fig. 2.4D shows a dramatic decrease in bedload flux during Event 5 while shear stress remains stable. It represents the same phenomenon shown in Fig. 2.3a between minutes 2 and 5. This decrease is repeated in Event 7 (Fig. 2.4E) in the left sampler. The flux-shear stress response for the right sampler (Fig. 2.4H) appears to be almost random.

Bedload texture

Similar to bedload flux, bedload texture varied not only between events (Table 2.2), but also fluctuated during each event (Fig. 2.4). Correlation coefficients between bedload texture and shear stress show no pattern. For the right sampler (Event 5) they are -0.5 for D_{90} and -0.32 for D_{50}. For Event 7 the respective values are 0.5 and 0.01. The regression coefficients between D_{50} or D_{90} and shear stress are low. For instance, r^2 values for the right sampler (Event 5) are 0.5 for D_{90} and D_{50}. For Event 7 the respective values are 0.35 and 0.15. These correlation and regression coefficients indicate that bedload texture varies considerably during an event, but the variability depends only slightly on shear stress.

Topographic changes

Table 2.3 summarizes bed topography data obtained after events using TLS and SfM. Data from both methods are available for Event 6 and A, with differences in depth of 5 and 4 mm. These values are within the maximum RMSEZ, thereby demonstrating that depth and volumetric comparisons between topographies by different methods are reliable.

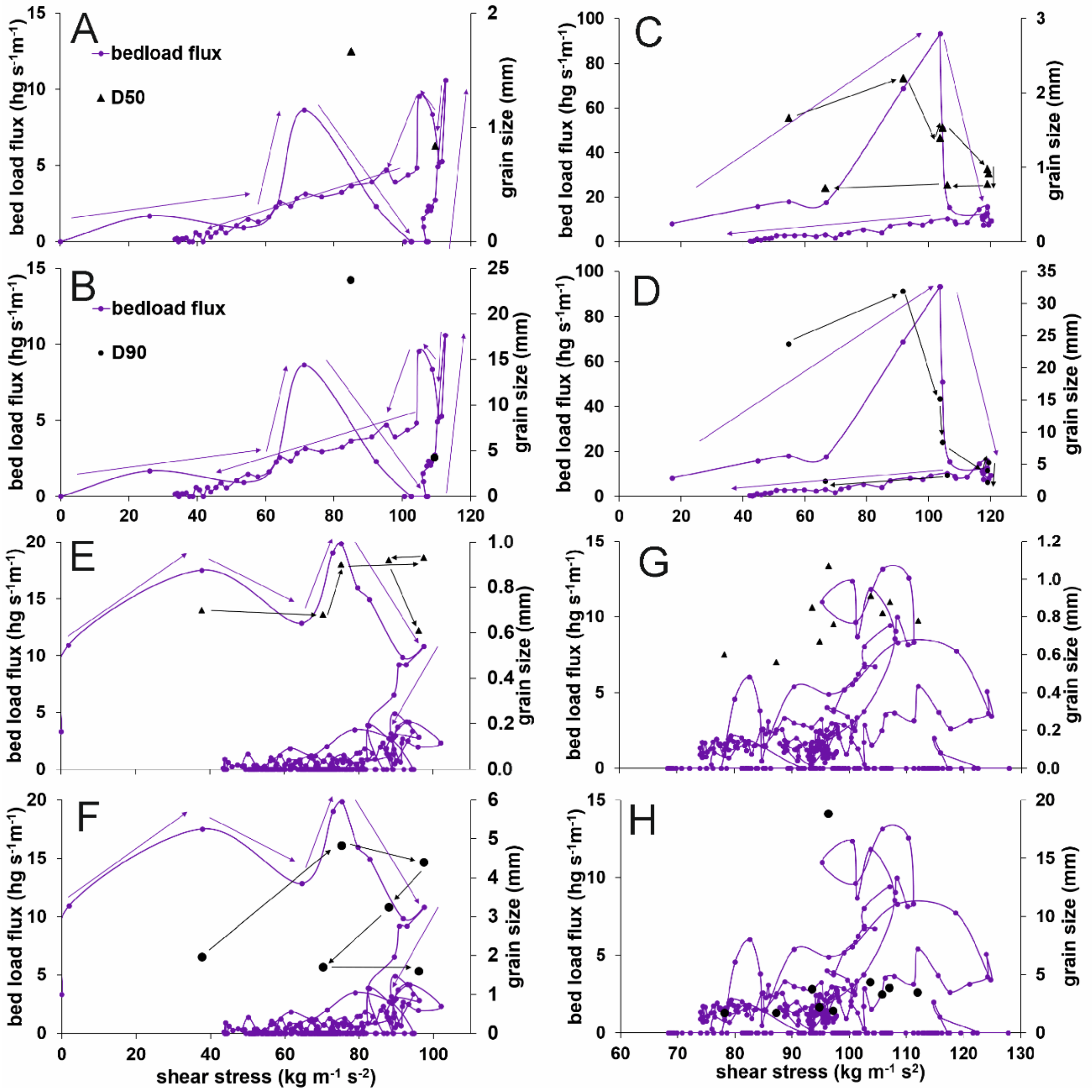

Figure 2.4. Examples of hysteresis of bedload flux and bedload texture vs shear stress in Event 5 (A-D) and Event 7 (E-H). A, B and E, F: left sampler; C, D, G and H: right sampler. The unit of bedload flux is hectograms/sm for ease of illustration.

Table 2.3. Comparison of TLS- and SfM-derived data of bed topography after bedload transporting events.

Event	method	difference in depth relative to previous topography	area change detection	error (+/-)	relative relief	texture		dominant bed texture		
						D_{50}	D_{90}	Thalweg	gravel and sandy gravel	sand and gravelly sand
		m	m^2	m	m	mm		%		
1	SfM	n.d.	n.d.	n.d.	0.21	25.4	53.2	77	19	4
3	LIDAR	+ 0.055	5.89	0.008	0.11	8	36.8	74	16	10
5	SfM	+ 0.019	5.20	0.005	0.11	6	14.7	88	6	6
6	SfM	- 0.006	3.41	0.005	0.10	6.1	15	69	9	22
6	LIDAR	- 0.001	3.59	0.005	0.10	6.3	16			
7	SfM	-0.014 (with 6-SfM) -0.017 (with 6-LIDAR)	4.20 (with 6-SfM) 4.16 (with 6-LIDAR)	0.005 (with 6-SfM) 0.005 (with 6-LIDAR)	0.13	15.4	48.3	53	14	33
A	SfM	- 0.007	5.26	0.004	0.19	15.4	49.4	72	22	6
A	LIDAR	-0.011	5.20	0.005	0.21	23.9	53.4			

n.d. - no data; A – after the 7th event for comparison of SfM to LIDAR.

In the case of GSD analysis, a significant difference has been found based on the topographies obtained for Event A (Table 2.3). Here the D_{50} is coarser for the TLS-based topography than for the SfM-based topography (23.4 vs 15.4 mm). This difference in roughness using both methods for the same topography has previously been reported (Smith & Vericat, 2015), suggesting that it is caused because the SfM dataset has higher precision than that by the TLS; it may also reflect Agisoft PhotoScan smoothing. In fact, SfM tends to smooth over some roughness elements, as may occur with boulders in a gravel bar, and as may occur with gravels of the Poveda Gully channel (Cook, 2017). However, the calculation of D_{90} yielded very similar values (53.4 mm for TLS vs 49.4 mm for SfM) as well as for D_{50} and D_{90} for Event 6. Similar results using both techniques have been reported for field plots and flumes (Morgan *et al.*, 2017; Smith & Vericat, 2015), both similar to the Poveda Gully channel.

Although topographic data are not available after all the events, we do have data after the most prominent events in terms of bedload flus (Table 2.2). This allows relating bedload flux and texture to topographic changes. Events 2 and 4 lack post-event topography but as bedload transport during these events was miniscule, we assume that significant changes in channel topography did not materialize due to these flow events.

Video camera

Four events were video recorded. Event 7 was recorded during the day and the quality is high. The other events were recorded at night; the light system allowed viewing the channel but the quality of the recoding is lower than during the day.

Appendix 1 depicts part of Event 5 between minutes 2-6 and 9-12 (see Fig. 2.3a) in fast velocity. Appendix 2 depicts part of Event 7 between minutes 0-10, 85-102 (see Fig. 2.3b) in fast velocity. Both recordings show how water and bedload enter the samplers as well as the topographic changes in the upstream feeder channel occurring during the events.

2.5. Analysis

Fluctuations in bedload flux

Explaining large spatio-temporal variations in bedload flux is a demanding task often undertaken using equations or flume experiments (Recking *et al.*, 2009; Lucía *et al.*, 2013). Under field conditions this has not been attempted in detail because of the difficulty in observing bedload motion. In this study we analyze temporal and spatial variations in bedload transport based on video recordings.

The following morphological changes occurring during Event 5 in the feeder reach immediately upstream of the slot samplers are observed (Appendix 1): i) a bar deflects almost all the water toward the right sampler, through a narrow thalweg (Fig. 2.5-A and Fig. 2.3a minute 2:33); ii) bar growth splits the water toward both samplers while the narrow thalweg becomes less pronounced (Fig. 2.5-B and Fig. 2.3a minute 11:39); iii) the bar further aggrades downstream towards the samplers and the thalweg is almost obliterated, having been filled with sediment (Fig. 2.5-C and Fig. 2.3a minute 20:30).

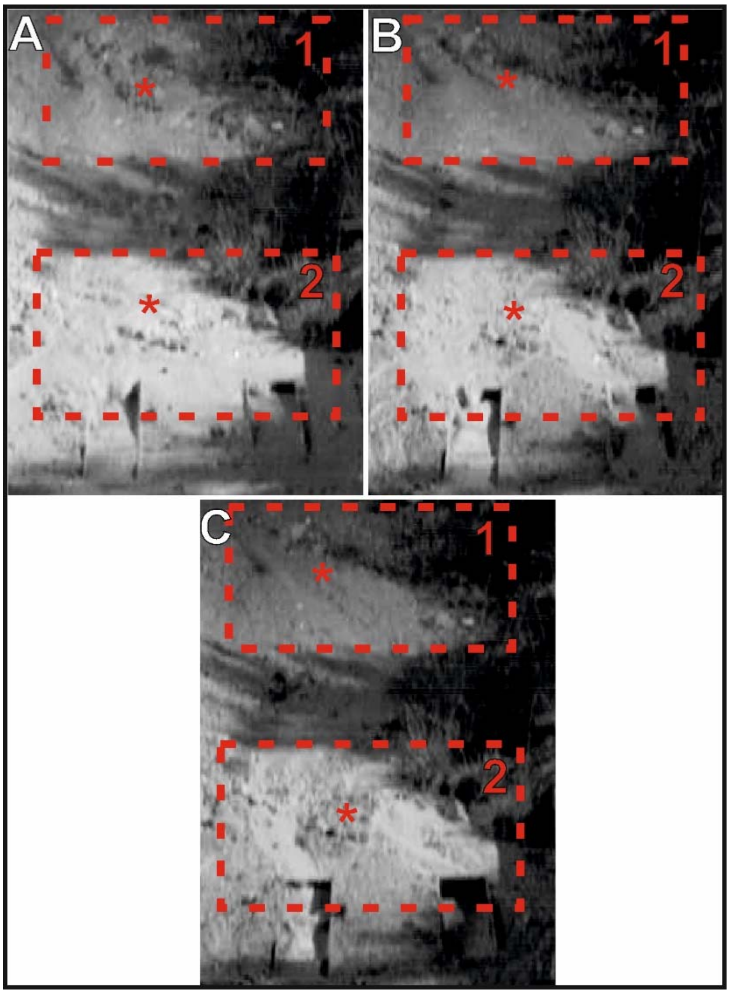

Figure 2.5. Topographic changes in the channel bed during Event 5 – see video recording Appendix 1. A the thalweg area is clearly defined (1) and the bar diverts the flow of water mainly toward the right sampler (2), minute 2:33. B the thalweg area is less clearly defined due to sediment filling (1) with water flowing towards both samplers, minute 11:39. C the thalweg area is not identified (1) view of the bar from which water is diverted toward both samplers (2), minute 20:30.

Likewise, the following morphological changes occurred during Event 7 in the feeder reach immediately upstream of the slot samplers (Appendix 2): i) the bar upstream of the right sampler diverts water and sediment toward the left sampler (Fig. 2.6-A and Fig. 2.3b minute 00:18); ii) the bar upstream of the right sampler has been eroded and most of the water is deflected to the right sampler, thereby giving rise to very high (peak) bedload fluxes (Fig. 2.6-B and Fig. 2.3b minute 9:33); iii); the most frequent bed morphology we have monitored in the channel is observed: most of the water and bedload are directed toward the right sampler while the left sampler attracts but a minor part of the flux of water and sediment (Fig. 2.6-C and Fig. 2.3b minute 13:02); iv) the right sampler is full (Fig. 2.6-D and Fig. 2.3b-minute 125:05) and although water flows toward, it the sensors register zero bedload flux. This entire sequence of images during Event 7 also shows how a low relief channel becomes incised.

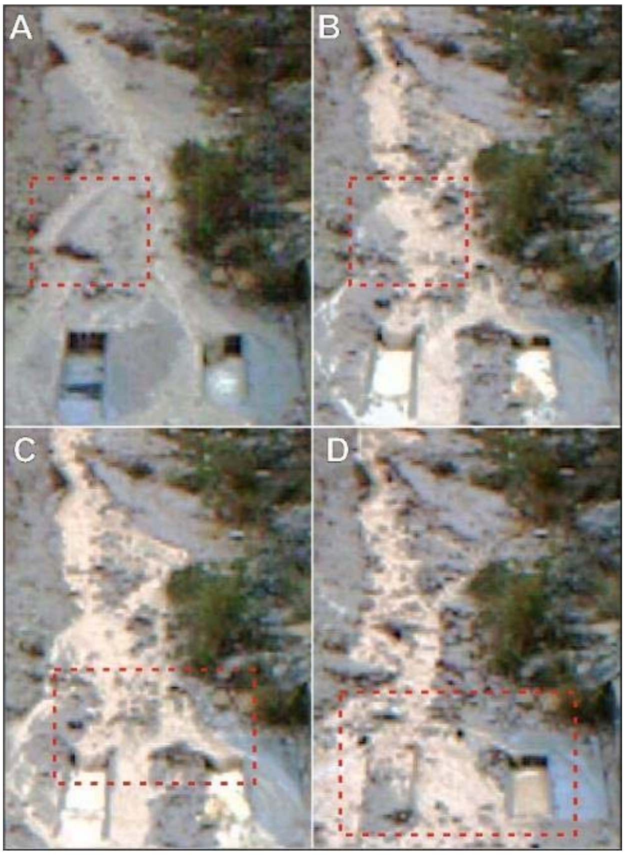

Figure 2.6. Topographic changes in the channel bed during Event 7 - see video recording Appendix 2. A the bar blocking the flow water towards the right sampler, minute 00:18 B the bar has been eroded of water flowing towards the right sampler, minute 9:33. C the most common situation in the Poveda Gully: more water flows towards the right sampler, minute 13:02. D the right sampler full of sediment (minute 125:05). This situation occurred only once during the study period.

Fluctuations in bedload texture

Pronounced variations in bedload texture are most notable in the event-varying magnitudes of D_{90} (Table 2.2). Events that occurred in autumn and summer are those that produced the largest D_{90} except Event 2, a very small event in terms of total mobilized bedload mass and maximum bedload flux. In contrast, events that occurred in winter and spring are characterized by small values of D_{90}. Event 5 was a spring exception, as it carried very large clasts (Table 2.2).

Morphological changes in the channel bed

The seasonal patterns in bedload texture (Table 2.2) can also be related to seasonal patterns in bed topography and surficial bed material texture (Table 2.3). Events that took place in winter and spring (3 and 5) are those associated with a low relative relief, filling the channel and small particle size in of the bed surface. Events occurring in autumn (1 and 7) have a high relative relief due to incision of the channel and coarser bed material. For Event 6 (summer) the topographic signatures in terms of relative relief and bed texture are complex, showing that incision has commenced (difference in depth, Table 2.3) but texture remains fine.

This annual cycle of topographic pattern in terms of relative relief related to incision/filling of the channel is demonstrated in Figs. 2.7 and 2.8, while Fig. 2.8 also shows the change in bed texture by way of surface roughness. Table 2.3 also shows how bedforms evolved between events. The highest event in terms of bedload mass and coarse texture (Event 1) has the smallest proportion of sand and gravelly sand bedforms and the largest proportion of gravel and sandy gravel bars; so does the next large autumnal Event 7 (Figs. 2.7, 2.8A, 2.8C, 2.8D). The only spring event with topography data, Event 5, has a small proportion of bars because it was filled by sand (Figs. 2.7, 2.8B, 2.8D).

The relative relief in Event 1 was much larger than at any other time. The difference in relative relief between Events 5 and 7 was not large, but thalweg width was much larger in Event 7. Thus, the cross-sectional shape in Event 5 describes a partial filling, leading to a wider, flatter thalweg in Event 7 (Fig. 2.7 and Fig. 2.8D).

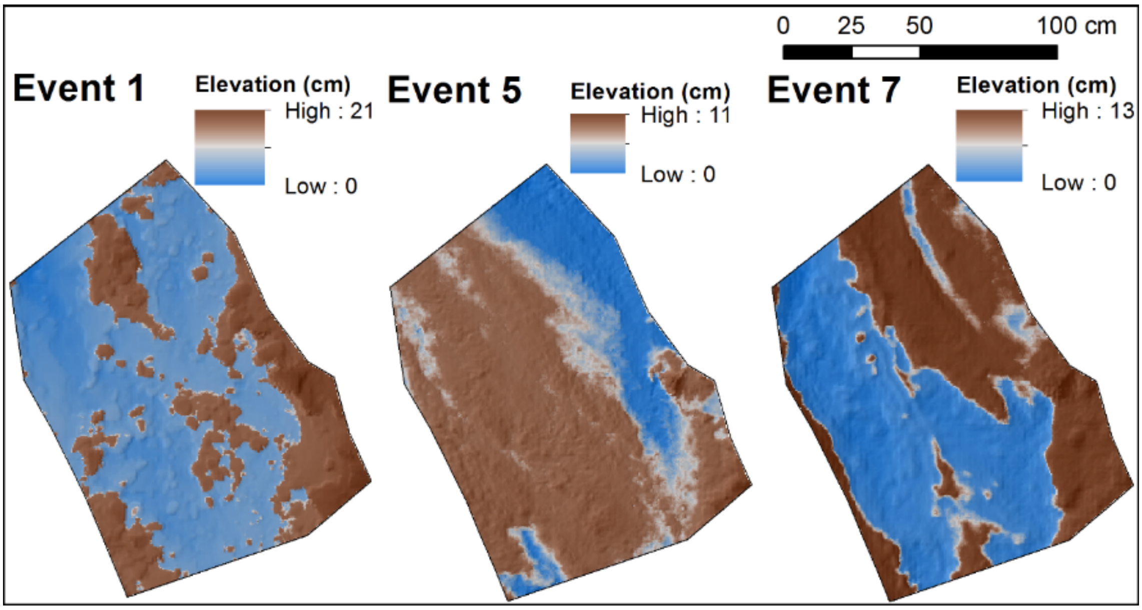

Figure 2.7. High resolution detrended digital elevation models of the feeder reach immediately upstream of the samplers after Events 1, 5 and 7.

2.6. Discussion

Spatiotemporal variations in bedload flux

Bedload transport has been demonstrated to be very variable cross-sectionally, and as it was monitored merely at two locations (the right and left samplers), the reported fluxes are local and do not represent the entire cross section. We do not attempt to calculate the channel-average bedload flux as done elsewhere with a larger number of samplers (Powell *et al.,* 1998; 1999), because the video evidence demonstrates that its variation across the channel is non-linear and temporally variable.

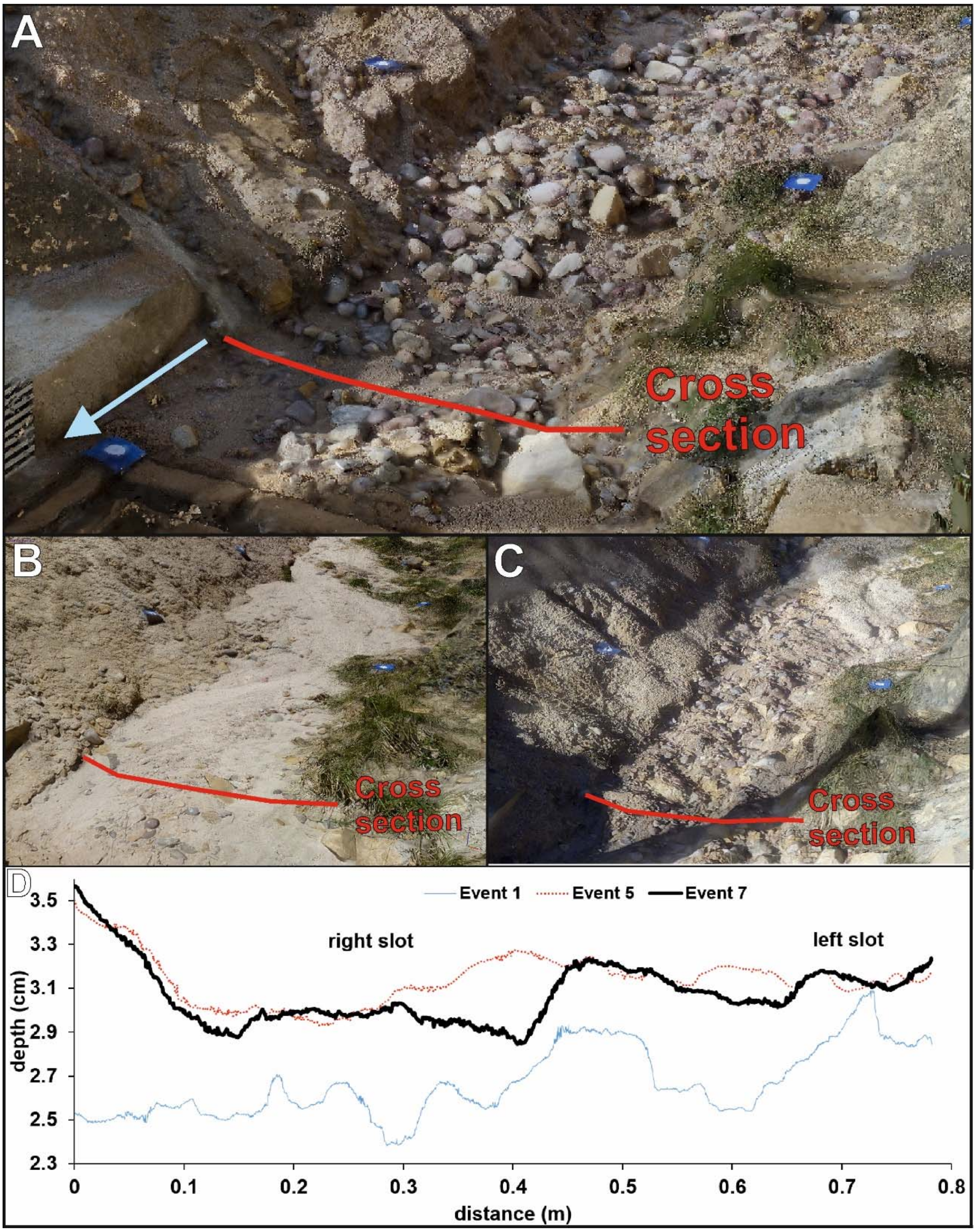

Figure 2.8. Topographic evolution of the stream bed upstream of the bedload samplers. A) after Event 1; B) after Event 5; C) after Event 7; D) SfM-based temporal changes of the cross sections in the immediate vicinity upstream of the samplers. The upstream view in these cross sections corresponds to the views in the photographs.

However, much has been gained from the evidence on the interrelationships between bedload and bed dynamics. The inclusion of variable proportions of gravel and sand lead to the formation and obliteration of gravel bars, thereby diverting water and bedload more so than in small sand-bedded channels (Lucía *et al.*, 2013).

The maximum registered local bedload flux (9.6 kg s^{-1} m^{-1}) is much higher than most published data for perennial rivers with maximum values rarely higher than 1 kg s^{-1} m^{-1} (García *et al.*, 2000; Habersack *et al.*, 2001; Laronne & Reid, 1993; Mao *et al.*, 2010; Vericat & Batalla, 2010). Nonetheless, it is lower than some other published bedload fluxes in ephemeral channels: 20 kg s^{-1} m^{-1} in the sandy Barranca de los Pinos (Lucía *et al.*, 2013) and 37 kg s^{-1} m^{-1} in the Moulin Ravine (Liébault *et al.*, 2016). The high bedload fluxes in these and other ephemeral channels occur due to fast recessions (Laronne & Reid, 1993; Hassan *et al.*, 2006; Storz-Peretz *et al.*, 2013) and large supply of sediment (Lucía *et al.*, 2013; Liébault *et al.*, 2016) leading to unarmored beds. Indeed, the gully wall is a nearby and large source of both sand and gravel, as demonstrated not only by the seasonal changes in the gravel/sand ratio (Table 2.3) as well as in the addition of sediment transported to the bed from the gully wall (e.g., last seconds of Appendix 2). The Poveda Gully channel has all these features, additional to involving large changes in the gravel/sand ratio of the channel bed. The existence of gravel in a narrow thalweg means that concentrated, deeper and faster water can transport gravel particles at altogether high bedload fluxes. However, these take place in a narrow part of the channel, whereas most of the channel bed experiences either no flow or very shallow flow with low bedload fluxes. When the channel is flooded with sand flow diverges over the entire cross section and flow depths are shallow. Hence, bedload flux is expected to be lower in the gravel-sand Poveda Gully channel in comparison to similarly steep sandy ephemeral channels such as the Barranca de los Pinos.

Hysteresis in bedload flux is not always observed (Powell *et al.*, 2003), although it has been frequently documented (e.g., Gomez *et al.*, 1989; Kuhnle, 1992; D' - Agostino & Lenzi, 1999b; Froehlich, 2003; Lee *et al.*, 2004). The abrupt changes in bedload flux produced by bar evolution are the cause for hysteretic responses in the Poveda Gully and may be the cause in other channels. Event 5 in the right sampler (Figs. 2.4C and D) is an example of this situation. Here, local bedload flux abruptly decreased although shear stress was very high - 10 kg m^{-1} s^{-2}. This stage coincided with a change in channel topography during minute 5 (Fig 2.3a). Appendix 2 demonstrates the topography upstream of the right slot between minutes 00:20 and 0:33 minutes. Hysteresis in the Poveda Gully is clockwise as documented in the Barranca de los Pinos (Lucía *et al.*, 2013).

Thus, the use of a video camera not only enabled observation of abrupt topographic changes, but also to understand the driver for hysteretic responses in bedload flux as well as the low correlations between bedload texture and shear stress.

Seasonal pattern in bedload texture and channel shape

Although the duration of our monitoring period was merely one year, a seasonal pattern has been identified in the channel (Fig. 2.9). Incision of the channel bed occurred in autumn events when much of the sand is depleted, leaving a rougher, sandy gravel bed. Spring and winter events are those when the channel becomes sandier while filling, thereby reducing its relative relief (Fig. 2.8 and Table 2.3). This seasonal pattern has been identified in other natural channels such as the Pasing-Potrero (Gran, 2012).

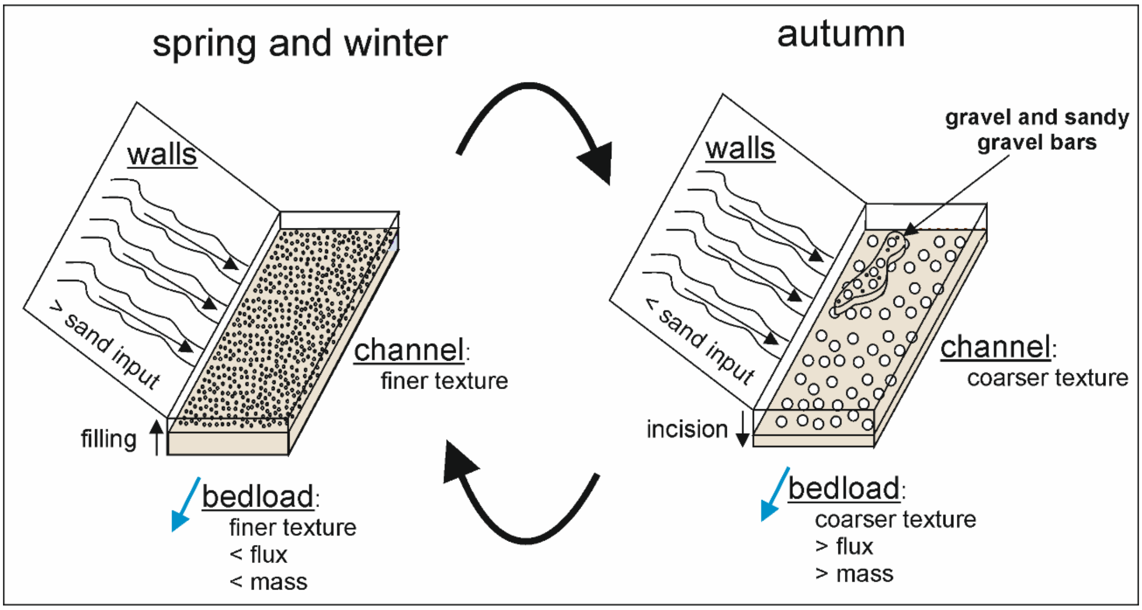

Figure 2.9. Seasonal cycle of bedload flux and texture and bed features in the Poveda Gully channel.

Topographic data are available after all the relevant bedload transporting events, hence bedload flux and texture can be related to the seasonal pattern in topography (Table 2.3). In autumn, the channel is incised and channel texture is coarser; flow events produced high bedload fluxes and coarse sediment. In contrast, in the spring and winter associated with periods of sand deposited in the channel, bedload fluxes decreased and bedload texture became finer (sandy). The summer event occurred in a transition period. These changes in topography and bedload flux can be associated with episodes of sand loading from the Poveda Gully walls, whichmainly comprise sand. Specifically, it seems that the channel is fed with sand in winter and spring due to freeze-thaw in the gully walls and rainfall-fed, thereby it is able to transport gravel-sized particles, producing high bedload fluxes in autumn (Figs. 2.7, 2.8). This role of sand in bedload transport has been studied not only in flume experiments (Wilcock *et al.*, 2001; Venditti *et al.*, 2010a), but also in natural channels (Whiting *et al.*, 1988; Gant, 2012).

Events 2 and 5 did not fully follow this pattern. Event 5 occurred in spring and although it generated channel fill similar to the other winter and spring events, it also produced high bedload fluxes of coarse texture. Even if the Poveda gully walls are primarily comprised of sand, they also contain gravel. Hence, it is possible that the texture of the sediment that fed the channel was gravelly, thus affecting bedload texture (Ferrer-Boix & Hassan, 2014). Although merely a conjecture, this may explain the high proportion of gravel in this event.

The autumnal Event 2 occurred between two events that incised the channel and during which yields of bedload were high. Event 2 generated low bedload fluxes of coarse texture despite the high rainfall intensity. This response may have arisen because sand was exhausted in the channels and shear stresses were insufficient to mobilize the gravel present in the channel, as documented in flume experiments (Wilcock & McArdell, 1997).

The importance of the sand supply in this cyclic seasonal pattern of bedload transport and topography is also manifested by the finer texture of bedload in comparison to the surface of each of the corresponding channel beds (Fig. 2.10). Bed texture in spring is sandy (Event 5) and gravelly in autumn (Events 1 and 7).

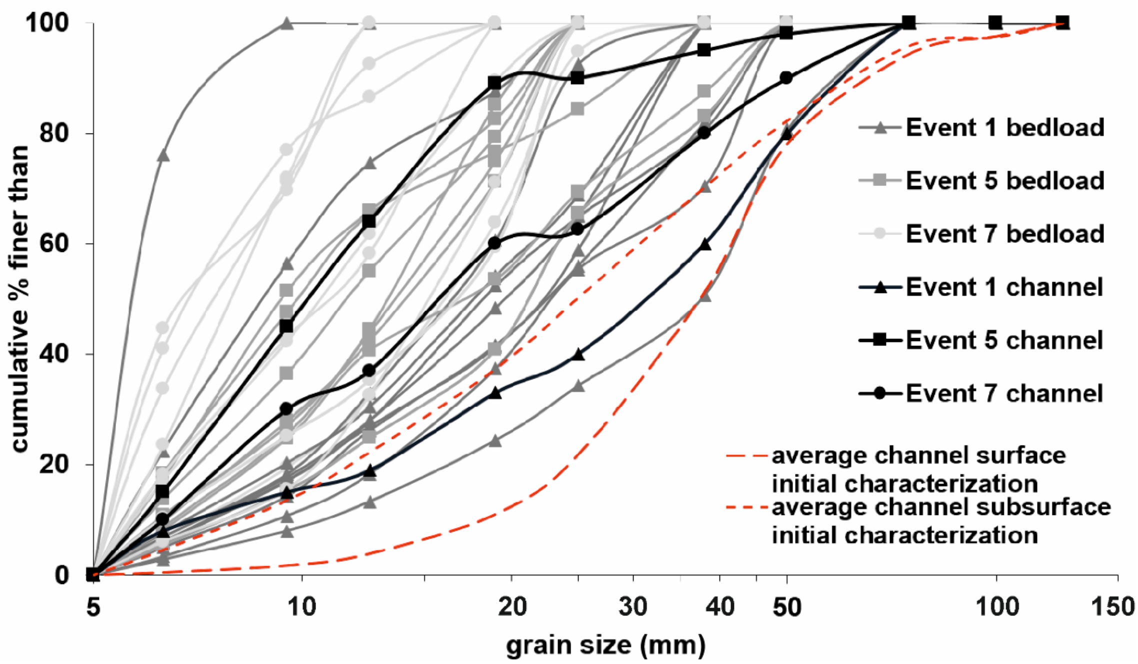

Figure 2.10. Sediment textures in the Poveda Gully for granule (> 5 mm) grain sizes of (i) the channel bed based on ToPCAT and (ii) bedload samples (right sampler) after events 1, 5 and 7; (iii) bedmaterial initial characterization. The distributions were lower truncated at 5 mm as this is the lowest denominator for both methods. The entire size distribution of the bedload samples is shown in Figure 2.2.

These significant changes in bed topography and texture between events as well as the dramatic changes in bedload flux can also be responsible for the low correlations between D_{50} and D_{90} and shear stress in Events 5 and 7.

The seasonally-variable supply of sand from the gully walls plays an important role in quantifying the interrelationships between morpho-textural changes in the channel and in bedload dynamics in such a gravel-sand fluvial environment. Nonetheless, sediment supply was not monitored in this study. Gully wall evolution should be quantified as the mass and texture of supplied sediment by accurately survey methods as done elsewhere (Lucía *et al.*, 2012). However, methods such as TLS and SfM have a given accuracy, and if gully walls supply sediment by unconcentrated mass wasting processes such as the fall of individual sand grains - for instance due to freeze and thaw - other methods – such as active sediment monitoring from walls will be required.

2.8. Conclusions

Through a combination of modern topographic techniques (SfM and TLS) and video recording, as well as the most un-intrusive method to continuously monitor and sample bedload flux and texture (Reid slot samplers), we have identified and quantified processes in a very active gullied landscape, a seasonally changing sand-gravel channel:

1. A seasonal pattern in bedload transport and morpho-texture has been identified in an ephemeral channel. The channel fills in spring and winter with sand having a low relative relief, but incises a narrow, coarse-grained thalweg in autumn. Although sand supply from the gully walls was not monitored, it appears that freezing-thawing in the gully walls and rainfall-fed spring and winter events contribute considerable sand that covers the gravel, fills the incised thalweg and causes the channel to become fine grained, most of it sandy.

2. Bar formation and obliteration play an important role in the copious cross-sectional variations in bedload flux and texture.

3. Gravel motion is considerably dependent on the presence of sand in the channel. Without sand, gravel remains immobile in all but very large flow events.

Acknowledgements

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Capítulo 3

Baseline to evaluate off-site suspended sediment-related mining effects in the Alto Tajo Natural Park, Spain

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Baseline to evaluate off-site suspended sediment-related mining effects in the Alto Tajo Natural Park, Spain

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Abstract

Mining is a human activity with considerable environmental impact. To evaluate such impacts, international laws require undertaking local studies based on direct sampling to establish baseline conditions of parameters modified by human activities. Mining takes place near the Alto Tajo Natural Park, where a suspended sediment concentration (SSC) baseline is required to determine whether mining affects water quality. To this end we have monitored the Tajo River and its tributary the Tajuelo following Before-After Control-Impact (BACI) techniques, recommended by Australian and New Zealand laws, requiring a specific method based on continuous monitoring and sampling to enable evaluation of SSCs. An SSC baseline has been defined at stations situated upstream of the mining area and compared with those downstream. The highest detected SSC upstream of the Tajuelo mines was 24 g l^{-1} whereas the highest simultaneous downstream value was 391 g l^{-1}, more than one order of magnitude higher than the supposed baseline (24 g l^{-1}). Additionally, this value is 1000 times more than the average concentration of 25 mg l^{-1}, used by the European Union until 2015, to guarantee the quality of salmonid waters. Following a BACI approach, a statistically significant SSC impact has been identified. The mined areas are the only source that can explain this increase. This is the first instance that such an increase and baseline have been found using this method. BACI is a simple and reliable method recommended for studying degraded areas rather than an irrelevant, fixed standard as included in most international laws.

Keywords: suspended sediment, BACI, mining activity, baseline, Natural Park

3.1. Introduction

Opencast mining impacts all ecosystem components: substrata, topography, hydrology, soil, vegetation, fauna, atmosphere and landscape (Soulard *et al.*, 2015; Tarolli & Sofia, 2016) and at mine sites there are on-site effects. In addition, mining activity can also have downstream off-site effects. Among these, the water quality impact associated with sediment discharged from mines to the fluvial system is one of the most detrimental (Martín-Moreno *et al.*, 2016; McIntyre *et* *al.*, 2016). Changes in sediment fluxes have been shown to have detrimental ecological effects on fish populations and their ecosystems, such as reduction in visibility and oxygen availability, temperature rise, breathing difficulties and damages in spawning beds (Robertson *et al.*, 2006; Kjelland *et al.*, 2015). Any and all these impacts can dramatically decrease fish and other organism populations. Furthermore, the increase in anthropogenic sediments can also damage the fluvial network in terms of infrastructures, such as roads and bridges or reduce the water capacity of reservoirs (Batalla & Vericat, 2011) and modify fluvial system dynamics, such as the deposition of bars and the dramatic increase in flooding (Pickup, 2008).

To evaluate whether mining off-site effects occur with respect to sediment dynamics, baseline parameters require definition. Once these baselines have been properly established, they can be used to compare before and after-mining impacts. This comparison can be undertaken through the so-called BACI (Before-After Control-Impact) technique (Smith, 2006).

Such control data are demanded by the European Commission (Directive 2006/44/CE) as well as by other public institutions worldwide, such as the United States Environmental Protection Agency (U.S. EPA, 2003a). Only the Australian and the New Zealand Environment and Conservation Council (ANZECC, 2000) law points out a specific method to monitor SSC impacts based on the BACI approach. Many additional studies highlight the need to undertake relevant measurements on this topic (Macklin *et al.*, 2006; Collins *et al.*, 2011; Nordstrom, 2015). These studies point out that baseline values have to be defined at the most local scale of the river. In mined areas, baseline definition has been studied widely in association with hydro-chemical properties (Yanguo *et al.*, 2002; Oyarzun *et al.*, 2011). Only few publications exist as far as a sediment transport baseline is concerned (Pentz & Kostaschuk, 1999; Chalov, 2014; Messina & Biggs, 2016). One of these is that on the Ngarradj catchment (Australia), for which a baseline of several parameters including Suspended Sediment Concentration (SSC) (Evans *et al.*, 2004) and for bed-material grain size (Saynor *et al.*, 2006) were defined. Both of these parameters are important to determine whether the sediment from mined areas modifies the sediment dynamics of the rivers in the Ngarradj catchment.

Other studies and relevant laws defined sediment-related baselines using a threshold value (U.S. EPA, 2003b). This is problematic because natural-fluvial sediment transport dynamics are complex and highly variable depending on a variety of parameters such as rainfall depth and duration, maximum rainfall intensity, peak flow, runoff occurrence and available sediment sources (Walling *et al.*, 2001; Alexandrov *et al.*, 2003; Rovira & Batalla, 2006; Nadal-Romero *et al.*, 2008; Regües & Nadal-Romero, 2013). Therefore, it is necessary to have a wide range of SSC values, representative of the different fluvial conditions, to provide a relevant baseline dataset.

Studies of suspended sediment have been undertaken worldwide. Some have monitored rivers taking into account the high variability of SSC during several hydrological years (Walling *et al.*, 2001; García-Ruiz *et al.*, 2008; López-Tarazón *et al.*, 2009). These have been accomplished to determine the total budget of catchments where human activity is significant, neither to establish a baseline nor to apply a BACI approach.

Our study seeks to be such a local study based on monitoring SSC in the kaolin mining area located near the Alto Tajo Natural Park (ATNP), Central Spain, by using BACI procedures. These are the most appropriate methods to study impacts described in an international law. We use the BACI with an aim, to improve a very narrow interpretation (fixing a limit of 25 mg l^{-1}) of the European law (Directive 2006/44/EC). The ideal manner to establish an SSC baseline to determine a likely impact due to mining activity would have been to measure each pair of stations, upstream and downstream of the disturbed area, before mining started and during its operation. This is impossible when mining began previously, as it did in the Alto Tajo in 1965 and holds for most mining areas worldwide, for which a pre-mining historic database is lacking. Another reliable method to establish an SSC baseline could have been the simultaneous monitoring of other catchments without mines but with features similar to those of the impacted streams. This is also impossible in our study area. We therefore chose a third recommended option: to install stations upstream and downstream of the potential mined sediment sources (Smith, 2006).

The principal aims of this study are: (i) defining the SSC baseline for forested areas (such as the temperate Mediterranean Tajuelo stream and the Tajo River) that receive water from mining areas; and (ii) evaluating if there is an impact in SSC associated with runoff derived from the mining areas. To accomplish these objectives an SSC Monitoring Network has been erected to record relevant data.

Our hypothesis is that following a BACI approach, it is possible to determine the SSC effect of mined areas.

3.2. Material and methods

Study Area

Alto Tajo Natural Park (ATNP) and mining area

The ATNP is located in East-Central Spain (Fig. 3.1). This protected area was established in 2000 by a regional law (DOCM, 2000) due to its outstanding biodiversity and particularly its high quality aquatic ecosystems. The ATNP area (105,721 ha) is characterized by plateaus and mesas capped by Cretaceous carbonate rocks (limestones and dolostones) underlain by sandy sediments, in which the Tajo River has incised a canyon system longer than 100 km and up to 400 m in depth (Carcavilla *et al.*, 2011). The sandy sediments contain the kaolin (Arenas de Utrillas Formation) exploited in several mines (Olmo & Álvaro, 1989; González Amuchastegui, 1993). Several kaolin mines very near the ATNP are located in the upper reaches of the stepped slopes. This activity began in 1965.

The most common soils are calcaric cambisols, mollic leptosols and rendzic leptosols on top of the mesas, and carbonate colluvia with calcaric cambisols on the slopes (IUSS Working Group WRB, 2007). The vegetation is representative of Mediterranean continental environments, with communities dominated by *Juniperus thurifera*, *Pinus nigra* subsp. *salzmanii* and *Quercus faginea* (MARM, 1997–2006).

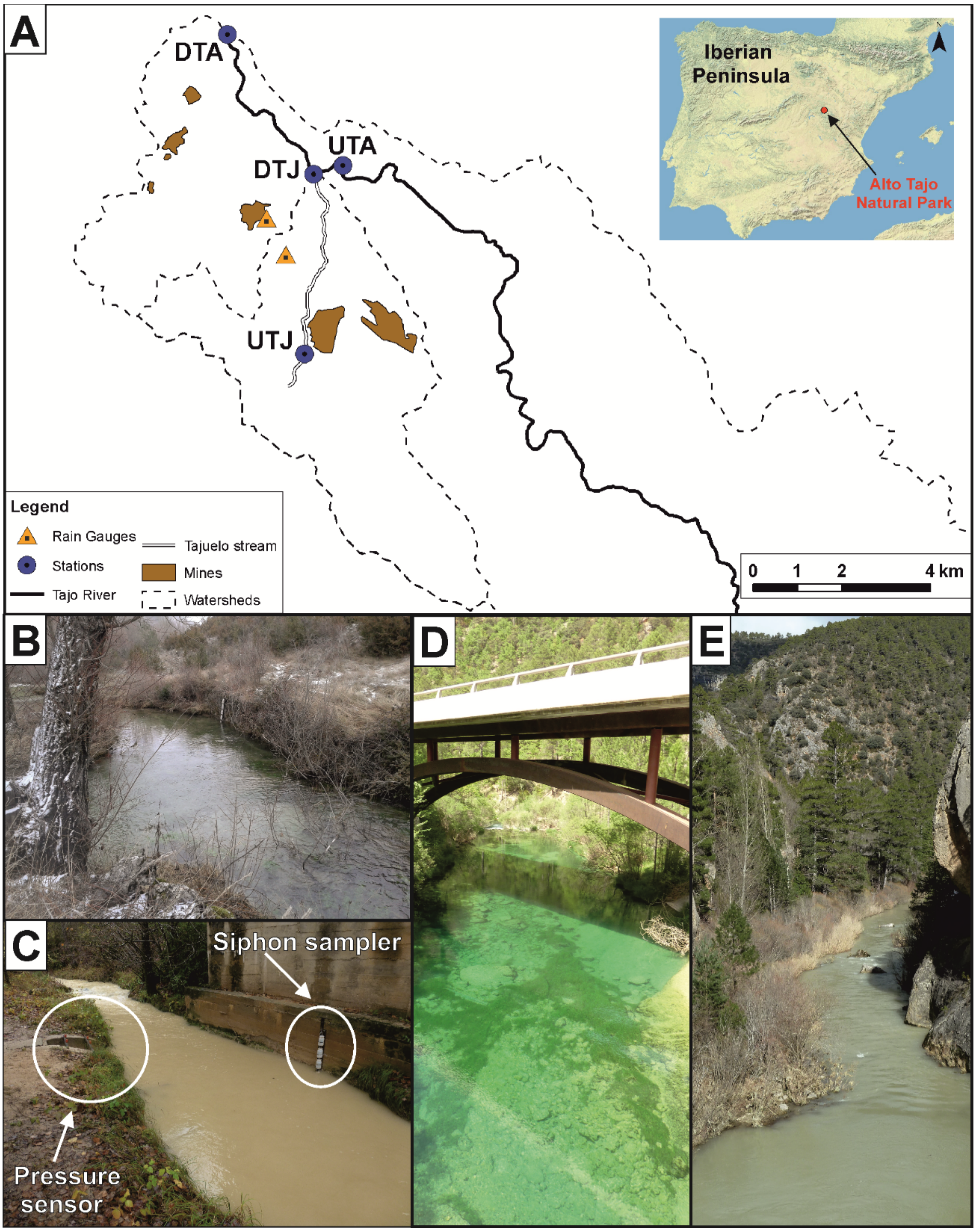

Figure 3.1. A: The SSC monitoring network in the Tajo River and Tajuelo stream. B: The Tajuelo upstream of the mining area (UTJ), C: The Tajuelo downstream of the mining area (DTJ), D: The Tajo upstream of the mining area (UTA), E: The Tajo downstream of the mining area (DTA).

The climate is temperate Mediterranean with dry and mild summers (Csb, according to Köppen 1918) and with a continental influence. Mean annual precipitation is 783 mm and mean annual temperature is 10 °C (AEMET, 2013). Seasonally, this area is characterized by long and cold winters with snow being common, and short and dry summers. The spring and fall are usually wet. The rainfall erosivity factor, R (equivalent to the R factor of RUSLE), is estimated to be about 800 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988).

Tajuelo catchment

The Tajuelo is one of the tributaries of the Tajo River (Fig. 3.1). With a 30 km^2 watershed area, the stream flows along 9 km at an average slope of 4% from an altitude of 1397 m above sea level (a.s.l) to the confluence with the Tajo River at 1033 m a.s.l. The bedrock of the upper part of the watershed is composed of limestones and dolostones, whereas the lower part is underlain by sandy sediments containing the mined kaolin (Weald and Utrillas Formation). This perennial stream has no gauging station; therefore, historic hydrologic data are unavailable. The only existing information is that measured during our monitoring activity between 2011 and 2013. For this period, stage rises typically occur in spring and fall with a recorded 33.9 m^3 s^{-1} maximum water discharge. Minimum flows (~0.06 m^3 s^{-1}) occur in summer.

The only village in the Tajuelo catchment is the small (0.08 km^2 with a population of 131) Poveda de la Sierra. Two mines are hydrologically connected to the Tajuelo. The María José mine (0.55 km^2) is active since 1965 and has sediment ponds that store the bedload eroded and transported within the mine, decanting most of the suspended sediment. The Nuria (0.62 km^2) mine is inactive since 2007, having neither ponds nor effective reclamation. In addition, there is one area at the confluence of the María José and the Nuria mines, with traditional reclamation (outslope-benches) directly connected to the fluvial network.

The studied Tajo River reach

The stretch of the studied Tajo River is located between Poveda and Peñalen bridges (Fig.3.1). The length of this stretch is 5.5 km with an average slope of 0.4%. Due to its low slope, its bankfull width (10 m) and its very low sinuosity, it is classified as pattern 2 (Schumm, 1981). Here carbonate precipitation is very common forming small tufa barriers. The nearest gauging station with historic discharge data (1945-2015) is the “3001 Peralejos de las Truchas”, located 15 km upstream of the upper sampling location on the Tajo. For this period the respective average mean and maximum annual discharges were 3.1 and 15.5 m^3 s^{-1} and the maximum water discharge was 258 m^3 s^{-1} (CEDEX, 2015; Confederación Hidrográfica del Tajo, pers. Comm., 2015).

Methods

We have only focused on SSC, not on bedload nor on solution because: (i) the mines are required to maintain sediment ponds that store all the bedload eroded from within the mines, and also for decanting at least some of the suspended sediment; (ii) the abandoned mines have to be restored in a manner that produces mostly sediment similar to the natural forested landscapes of the surroundings; and (iii) the dissolved component has minor geomorphic and hydrologic relevance in the mining areas.

Sampling design: monitoring network and BACI techniques

Two recording stations were installed in each river, four in total (Fig. 3.1): two stations upstream of the mining areas (UTJ: Upper Tajuelo, UTA: Upper Tajo) and two downstream of them (DTJ: Downstream Tajuelo, DTA: Downstream Tajo). The data from the upstream stations were used to define the baseline. The BACI methodology requires a baseline: a database of instantaneous water samples used to establish trigger values: if these are surpassed, authorities or companies can investigate unacceptable values and to decide how to avoid this condition. We thus focused on instantaneous values rather than mine-related before-after sediment yields. Yields are useful to quantify the entire impact of a given activity, but not to generate data for alarms. The downstream stations were compared with the upstream ones to quantify the impact of mining areas. BACI techniques are based on spatial comparison of pairs of samples taken in rivers at "the same time" before and after receiving water from the mined areas. Its aim is not to study the sediment dynamics of a catchment with respect to human activities, but to quantify the impact of one specific present activity in a given river reach. It requires an identical and contemporaneous sampling methodology.

Field equipment, monitoring and lab procedures

Rainfall was measured by two recording tipping-bucket rain gauges (Davis *Rain Collector II*) installed in the area (Fig. 3.1). Water level (discharge) and SSC were monitored during the 2012-2013 and 2013-2014 hydrological years (1 October – 30 September). Water depth in the Tajuelo was recorded every 10 min by a pressure sensor (Global Water WL16) at DTJ (Fig. 3.1). Water level data were transformed to discharge by a stage-discharge rating curve. Discharge was determined by the product of average velocity (electromagnetic current meter, Flo-Mate 2000 of Hach) and cross sectional wetted area (Whiting, 2003). As the pressure sensor broke down during 15/03/2014-02/07/2014, we made use of rain gauge and weekly field reports as well as continuous discharge from the nearby Merdero Catchment to define to which event and each sample belonged. The Merdero catchment area is a half of the Tajuelo's, but their runoff response is quite similar in terms of number and relative size of flow events. The possible differences were corrected with the weekly field data. For the Tajo we used data recorded by the Tajo Water Authorities at the 'AR02 *Tajo en la Rocha*' gauging station (Confederación Hidrográfica del Tajo, pers. comm., 2015), located 9 km downstream of DTA. We also used two pressure sensors (Mini-Diver at UTA and Rugged Level Troll 100 at DTA) corrected for barometric pressure (Rugged BaroTroll).

SSC was determined by direct sampling at each station using two different methods: (i) manual sampling by the depth-integrating approach (Hicks & Gomez, 2005) and (ii) automatic sampling with siphon samplers (Graczyk *et al.*, 2000) - bottles situated at different fixed heights on a channel bank high enough above the bed to exclude bedload entry (Fig. 3.1). Cross section and depth integration calibration were not undertaken because they are not required in the BACI. Imperative for this study was the guarantee that the samples were contemporaneously taken by the same method and cross sectional sampling position.

The four stations were visited weekly and sampled by depth integrating while bottles of the siphon samplers were replaced when necessary. Most of the manual samples were self-evidently collected during base flow. Those from the siphon samplers represent rising stages. Altogether 403 samples are available (Table 3.1). For each of the streams there was no correspondence in the number of samples taken upstream and downstream due to several factors:

(i) At times the number of samples filled in siphon samplers were unequal (e.g., location may have had one bottle more or less than the other due to the varying water heights at each location);

(ii) some siphon samplers were lost because a bottle was torn from the sampler by fast flows;

(iii) at times stream conditions prevented undertaking manual depth integration sampling in one of the stations but not in the other.

Approximately 0.5 L of water was sampled and dried in the laboratory to determine the SSC.

Data analysis

Each sample was identified by time, date, location and stage (base flow, rising limb or recession). Siphon samples were related to continuously logging water stage and stage sensors. Although in each stream we use water discharge data measured by different stage sensors, the number of events recorded by them are identical as required by the BACI technique.

Table 3.1. Summary of number of samples taken at each sampling location.

hydrogaph segment	location	Tajuelo 2012-13	Tajuelo 2013-14	Tajo 2012-13	Tajo 2013-14
base flow	u/s	33	37	35	33
	d/s	33	38	n.d.	32
rising	u/s	19	13	30	14
stage	d/s	23	6	n.d.	15
recession	u/s	8	4	3	7
	d/s	8	5	n.d.	7
total		124	103	68	108

u/s: upstream of mines, d/s: downstream of mines, n.d.: no data.

In order to define the baseline, the SSC database for stations UTA and UTJ were processed to calculate maximum, minimum and average values with regard to stage and season. Had the number of samples been much larger a differentiation based on sampling methodology could have been made. However, these calculations were made for SSC data derived from both depth integration and siphon samples. Using the BACI technique, we assume that the SSC data measured in upstream stations represent water without runoff from mining areas. These were compared to SSC data derived from stations located downstream of mining areas. For each stream we constructed a paired SSC database of contemporaneous UTA-UTJ and DTJ-DTA; the pairs were either only from depth integration or only form siphon sampling techniques. A student t-test was applied to each set (as common in other BACI studies – see Smith, 2006) assuming as null hypothesis that the mean difference between each data pair is 0 and, therefore, no SSC increase occurs due to mining. Each of the two compared samples derive from the same stream, hence they are paired. In these cases, the technique is known as BACIP, Before-After Control-Impact Paired (Wheater & Cook, 2005; Smith, 2006).

3.3. Results

Water discharge

During the monitoring period there were 37 flow events of which 20 occurred in the first year and 17 in the second. In the Tajuelo mean discharge was 0.6 $m^3 s^{-1}$ during the first year for which data are available. In the Tajo the mean water discharge was 9.6 and 6.8 $m^3 s^{-1}$ during the first and second years, respectively. Maximum instantaneous discharges for these years were 33.8 and 70.5 $m^3 s^{-1}$ for the Tajuelo and Tajo River, respectively. Runoff volume for the Tajo was 303.7 hm^3 the first year and 232.6 hm^3 the second. For the Tajuelo the first year runoff volume was 29.4 hm^3. Fig. 3.2 shows hydrographs for the Tajuelo stream and the Tajo River.

This study lasted two years. To what extent is it representative of past years? The respective mean and maximum instantaneous water discharges during the study period were 3.4 and 74.6 $m^3 s^{-1}$ as recorded at the '3001 Peralejos de las Truchas' gauging station (CEDEX, 2015; Confederación Hidrográfica del Tajo, pers. comm., 2015). Fig. 3.3 shows a comparison of the peak discharge of the study period with the historic database of peak discharges. The latter is available for the Tajo River station 3001 located upstream of our study area. The maximum instantaneous water discharge in our study period is almost identical to the long-term maximum instantaneous water discharge. Therefore, we deduce that our results are representative.

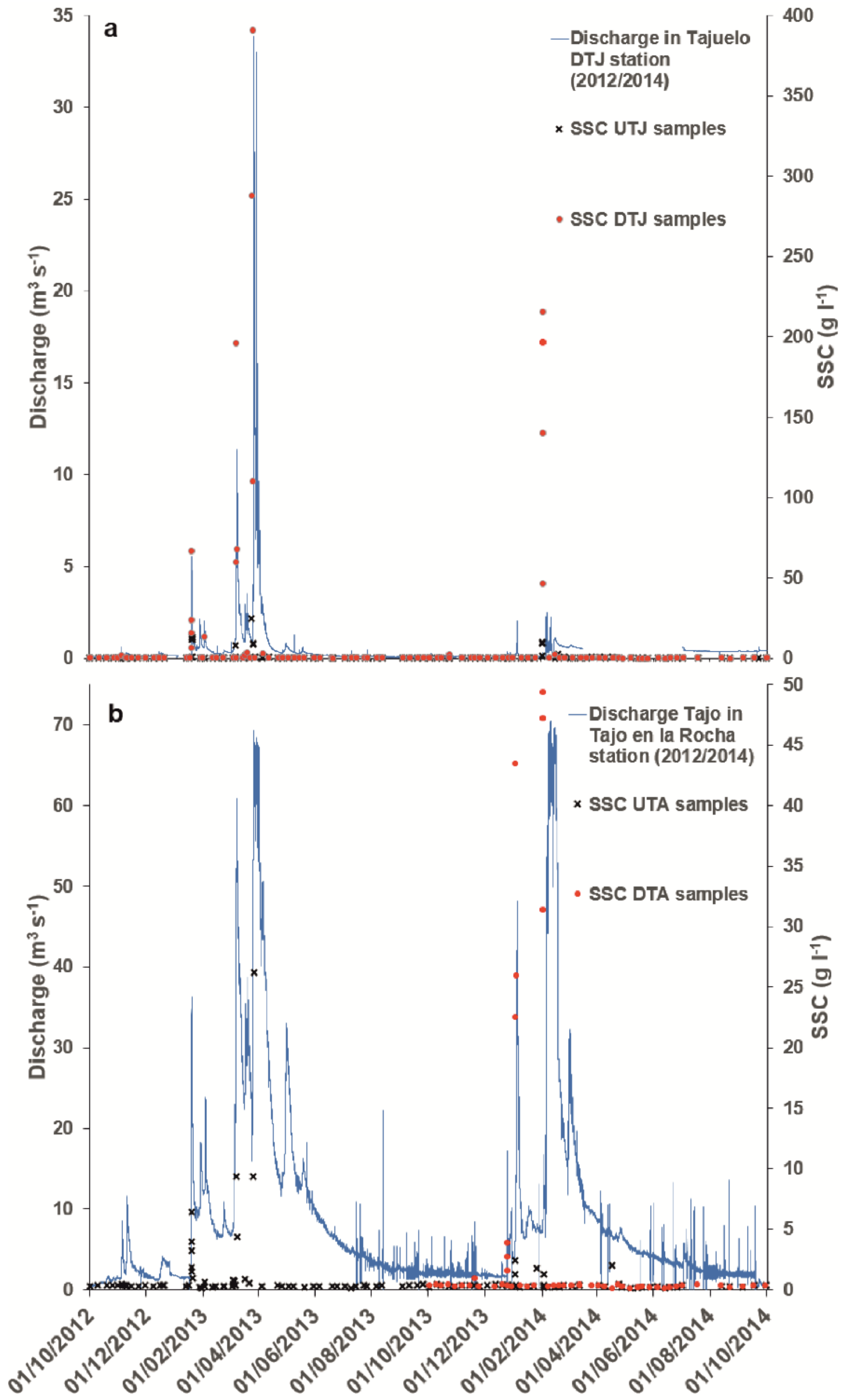

Figure 3.2. Hydrograph and SSC for the Tajo (a) and the Tajuelo (b) during the 2012-2013 and 2013-2014 hydrological years. DTA samples are available for the Tajo only for the second hydrological year. All UTA samples were used to define the baseline and only the second year samples were used to undertake the UTA-DTA comparison. Due to lack of Tajuelo discharge data for the period 15/03/2014-02/07/2014, the timing of samples on rain gauge and discharge data were determined from the nearby Merdero stream.

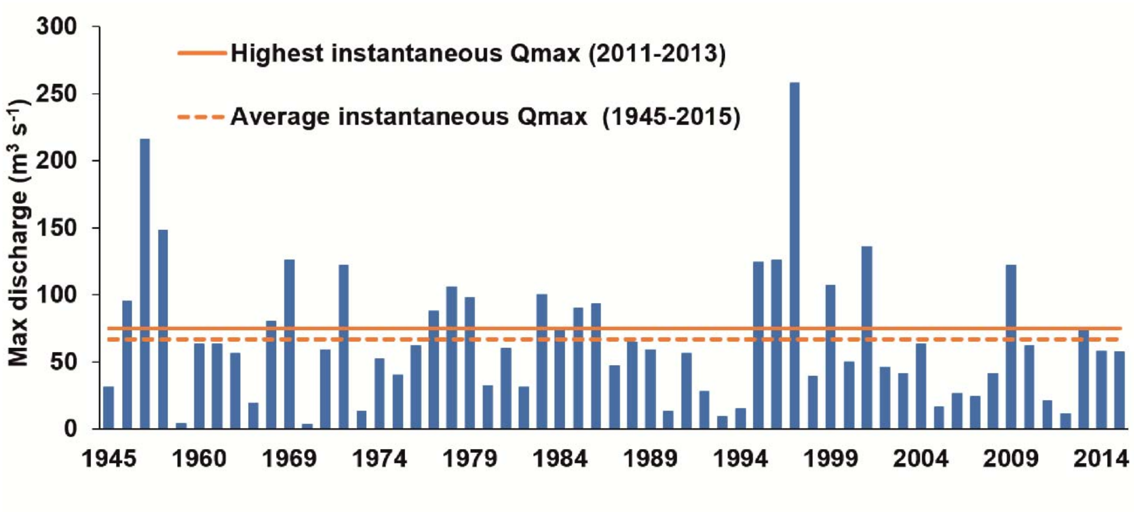

Figure 3.3. Maximum instantaneous water discharge for the 1945-2015 data series at the "3001 Peralejos de las Truchas" gauging station (CEDEX, 2015; Confederación Hidrográfica del Tajo, pers. comm., 2015). The horizontal lines are the highest instantaneous discharge: the full line refers to the period recorded during the study period and the dashed line to the mean for 1945-2015.

Comparison of SSC at upstream vs downstream stations

We acquired samples from 24 events; 15 from the first year and 9 from the second. Twelve rises (4 from the first year and 8 from the second) were too small to be sampled because water level rise was insufficient to fill the bottles. One event was not sampled as personnel were unavailable. In total, 105 pairs of samples for the Tajuelo and 50 for the Tajo were collected. DTA samples are available only for the second hydrological year. All UTA samples were used to define the baseline and only second year samples were used to the UTA-DTA comparison.

Four stations have similar values of SSC up to the third quartile (Table 3.2). In contrast, the maximum values differ markedly, especially downstream of the mining areas. Upstream of the mining areas the maximum registered SSCs are similar: 24.4 g l^{-1} in the Tajuelo and 26.2 g l^{-1} in the Tajo. In contrast, the maximum

SSC downstream of the mining areas was 52.4 g l^{-1} in the Tajo and 391 g l^{-1} in the Tajuelo. Fig. 3.4 shows a comparison among the highest values of SSC sampled in the rising limb of flow events that occurred during the study period, including only 15 - those for which samples were available in both stations.

Table 3.2. Descriptive statistics for suspended sediment concentration (g l^{-1}) in the Tajuelo and the Tajo for the 2012/2013 and 2013/2014 hydrological years.

parameter	Tajuelo		Tajo	
	upstream	downstream	upstream	downstream
n	114	113	122	54
n manual samples	95	88	90	44
n siphon	19	25	32	10
mean	1.24	16.8	0.92	2.66
StDev	3.33	56.5	2.70	13.6
minimum	0.07	0.06	0.13	0.10
median	0.34	0.32	0.35	0.33
3rd quartile	0.42	0.57	0.41	0.40
maximum	24.4	391	26.2	52.3

Maximum SSC values registered in each pair of stations for a single event (see Table 3.3) are a16-fold increase in event 15 on the Tajuelo and a 38-fold increase in event 27 on the Tajo. These increases are statistically supported by applying a student t-test according to the BACIP technique to each data series. For the Tajuelo there is a significant difference ($p < 0.01$) between the samples taken at UTJ and at DTJ at the 99% confidence level. Similarly, in the Tajo ($p < 0.01$) there is a significant difference between the UTA and DTA samples at the 92% confidence level. Table 3.3 also shows SSC for one of the events with insignificant rises.

Table 3.3. Comparative response of SSC at the upstream and downstream sampling locations on the Tajuelo and Tajo for three flow events during the 2012/2013 and 2013/2014 hydrological years.

	event features						rising stage			
event	date	river	Q mean	Q peak	number of peaks	location	max SSC	mean SSC	number of samples	event rainfall
#			$m^3 s^{-1}$	$m^3 s^{-1}$	#		$g l^{-1}$	$g l^{-1}$	#	mm
15	25.03.13	Tajuelo	9.14	33.9	6	u/s	24.4	10.6	4	97.8
						d/s	391	197	4	
		Tajo	43.6	69.3	4	u/s	26.2	12.0	3	
						d/s	n.d.	n.d.	n.d.	
27	01.02.14	Tajuelo	n.d.	n.d.	1	u/s	9.69	6.67	3	41
						d/s	215	149	4	
		Tajo	9.42	16.8	1	u/s	1.3	0.70	3	
						d/s	49.3	42.6	3	
30	24.04.14	Tajuelo	n.d.	n.d.	1	u/s	0.44	0.44	1	9
						d/s	0.38	0.38	1	
		Tajo	5.86	7.68	1	u/s	0.43	0.27	2	
						d/s	0.40	0.40	1	

u/s: upstream of mines, d/s: downstream of mines, n.d.: no data.

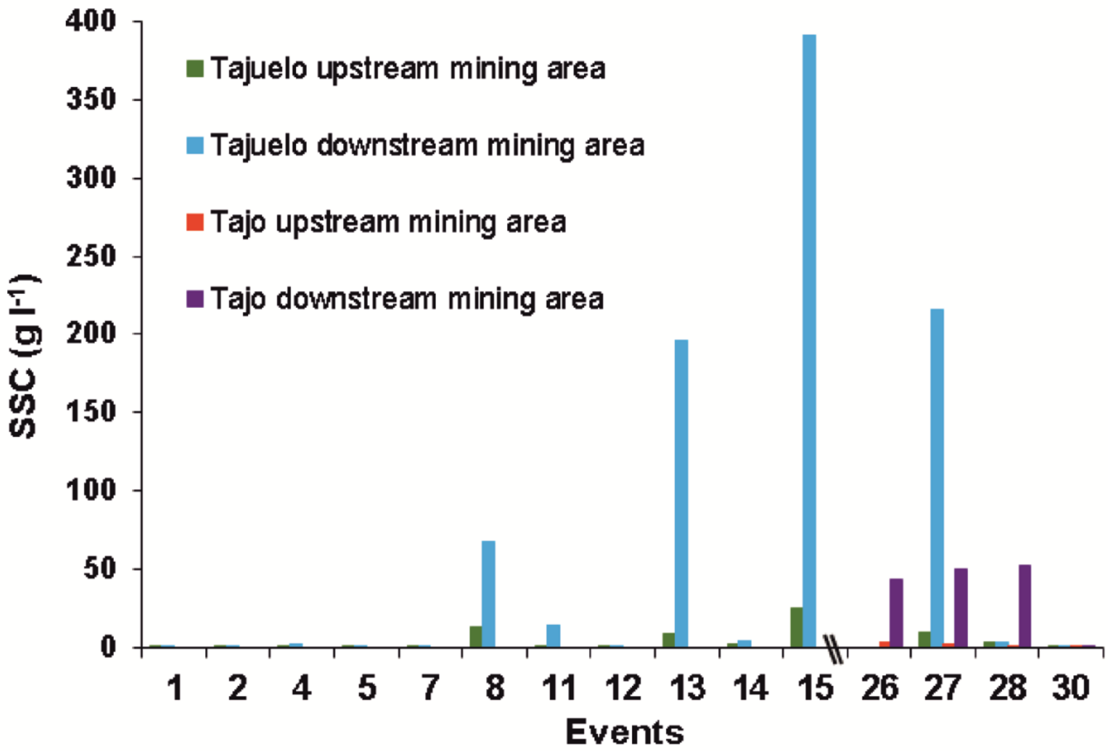

Figure 3.4. Comparison among the highest values of SSC sampled in rising limbs during the 2012-2013 and 2013-2014 hydrological years.

Baselines for the Tajo River and the Tajuelo Stream

The upstream stations are very similar with regard to mean, coefficient variation and maximum values of SSC (Table 3.2). The SSC baseline is defined for the Tajuelo and the Tajo by values summarized in Table 3.4. Maximum values occur on the rising limb of winter-spring events; the lowest in summer base flow. Summer rainfall events were insufficiently intense or lengthy to produce water level rises in either stream.

Table 3.4. The Tajuelo and Tajo baselines. Hydrological years 2012/2013 and 2013/2014.

	hydrograph segment	Tajuelo				Tajo			
		max SSC	min SSC	mean SSC	number of samples	max SSC	min SSC	mean SSC	number of samples
		$g\ l^{-1}$	$g\ l^{-1}$	$g\ l^{-1}$		$g\ l^{-1}$	$g\ l^{-1}$	$g\ l^{-1}$	
autumn	base flow	0.43	0.13	0.30	24	0.45	0.23	0.37	26
	rising stage	0.31	0.31	0.31	1	0.43	0.28	0.31	6
	recession	0.34	0.34	0.34	1	0.33	0.33	0.33	1
winter	base flow	0.5	0.24	0.34	14	1.73	0.27	0.47	12
	rising stage	12.9	0.21	3.46	15	6.42	0.19	1.13	24
	recession	0.35	0.28	0.31	3	0.35	0.13	0.22	6
spring	base flow	0.93	0.22	0.40	15	1.97	0.16	0.39	12
	rising stage	24.4	0.39	3.52	9	26.2	0.11	2.55	13
	recession	0.75	0.21	0.42	6	0.56	0.25	0.34	6
summer	recession	0.43	0.07	0.29	18	0.38	0.17	0.29	16
	rising stage	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	recession	n.d.	n.d.	n.d.	n.d.	0.14	0.14	0.14	1

n.d.: no data.

3.4. Discussion

The BACI approach

There are few studies (Walling & Fang, 2003; Messina & Biggs, 2016) where mining impact on SSC has been measured. Some of them were undertaken by establishing annual sediment loads for a whole catchment. They show that total sediment loads continuously increase for the entire catchment, but no evidence is available as to where mining runoff is produced. Few other studies (Balamurugan 1991; Chalov, 2014) compared the annual sediment load following the before-after mining impact scheme, thereby identifying the impact using SSC-Q or NTU-SSC rating curves. These analyses allow identification of an SSC impact, but they do not establish trigger values to allow comparison with future mining runoff. There is only one study available where BACI was applied to study mining activity over SSC (Evans *et al.*, 2004), though no effect was found by comparing paired samples.

The BACI approach is a simple method whose aim is not only to study an impact from a specific river location by comparing contemporaneously paired samples, but also to determine local trigger values. It is simple though it does not replace wide studies of sediment dynamics and yields. Instead, it is a useful and realistic tool that can be easily applied by water authorities and mining companies to establish the effect of mining runoff, taking into account that in most of the cases the data are urgently needed. Despite its simplicity, it has hitherto been required only by Australian and New Zealand authorities. All other countries have laws and regulations that do not clearly take into account the high natural variability of SSC.

Effect of mining areas on SSC

The potential effect of mining areas on downstream values of SSC is based on all the events with the exception of 12 events having insignificant small rises. Table 3.3 includes data for one of those insignificant events (number 30) with no interstation increase in SSC.

A comparison between the max SSCs in the Tajuelo and Tajo with those in other environments is shown in Table 3.5. The other examples are rivers in Mediterranean areas draining different land uses: forested, abandoned cultivated areas, agricultural fields or those draining badlands. Moreover Table 3.5 shows rivers draining catchments with mining activity.

Table 3.5. Maximum SSC in in the Alto Tajo Natural Park compared with: (i) various Mediterranean catchments; (ii) catchments with mining activity.

	catchment	max SSC	area	land use	reference
		g l^{-1}	km^2		
Alto Tajo Natural	Tajuelo d/s	391	28.7	forested fields with abandoned cultivated areas, small villages, some slope gullies and mining activity	This study
	Tajuelo u/s	24.4	18.6		
	Tajo d/s	52.3	537		
	Tajo u/s	26.2	484		
Mediterranean	San Salvador	1.9	0.92	undisturbed forest environment	García-Ruiz *et al.* (2008)
	Arnás	16.0	2.84	abandoned cultivated area subjected to colonization by plants	Lana-Renault & Regüés (2009)
	Araguás	500	0.45	badlands	Nadal-Romero *et al*. (2008)
	Ca l'Isard	174	1.32	forested with some badlands	Soler *et al*. (2008)
	Barrendiola	1.6	3	forested	Zabaleta *et al*. (2007)
	Can Vila	8.6	0.56	mainly abandoned agricultural fields and forests	Soler *et al.* (2008)
	Isabena	357	445	having patches of highly erodible areas (i.e., badlands)	López-Tarazón *et al.* (2009)
	Enxoé	3.8	60.8	agricultural fields	Ramos *et al.* (2015)
	Tordera	1.0	894	forested	Rovira & Batalla (2006)
mining areas	Haggart Creek and Mc Questen River system	0.3	n.d.	forested area with gold mines	Pentz & Kostaschuk (1999)
	Vyvenka	2.7	13000	opencast platinum mine	Chalov (2014)
	San Francisco Bay Coastal	0.14	n.d.	urbanized estuary impacted by numerous[1] anthropogenic activities.	Buchanan & Morgan (2012)
	Ngarradj	0.1	0.13	mining activity adjacent to Kakadu National Park	Evans *et al.* (2004)

[1] *Mining legacy, channel dredging, aggregate mining, reservoirs, freshwater diversion, watershed modifications, urban runoff, ship traffic, introduction of exotic species, land reclamation, and wetland restoration*

u/s: upstream of mines, d/s: downstream of mines, n.d.: no data.

The maximum SSC values of UTJ and UTA are similar to the maximum SSC values measured in Mediterranean catchments typical of abandoned agricultural and forested areas, for instance the Arnás catchment (Lana-Renault & Regüés, 2009). The maximum SSC in the DTJ is similar to that measured in other Mediterranean catchments with badlands, such as Isábena (López-Tarazón *et al.*, 2009), Araguás (Nadal-Romero *et al.*, 2008) or Ca l'Isard (Soler *et al.*, 2008). It is also as high as concentrations measured in rivers draining mining areas (Pentz & Kostaschuk, 1999; Chalov, 2014).

Explaining the increase between both pairs of stations is complicated owing to the fact that there are several potential sediment sources that can explain the difference in SSC between stations located upstream and downstream of mining areas. The Tajuelo catchment contains five such potential sources: the village and related activities, gullies, agriculture, mines and the rest of the catchment (Fig. 3.5 and Table 3.6). By far the largest area (95%) contributing sediments is that of forests and abandoned agricultural lands recolonized by vegetation or reforested. For Mediterranean areas these tend to produce comparatively low values of maximum SSC in the range 1-16 g l^{-1} (Table 3.5). The area of the Poveda village comprises 0.33% of the Tajuelo Catchment. There is no active construction in the village nor are there indications of gullying or channel widening downstream of the village, from which we deduce that its contribution to catchment sediment is negligible. There is a single prominent gulley above the village – the Poveda Gully – and few very minor gullied areas in its vicinity. The total gullied area encompasses less than 0.01% of the Tajuelo Catchment. Very small gullied areas can be responsible for high increases in SSC.

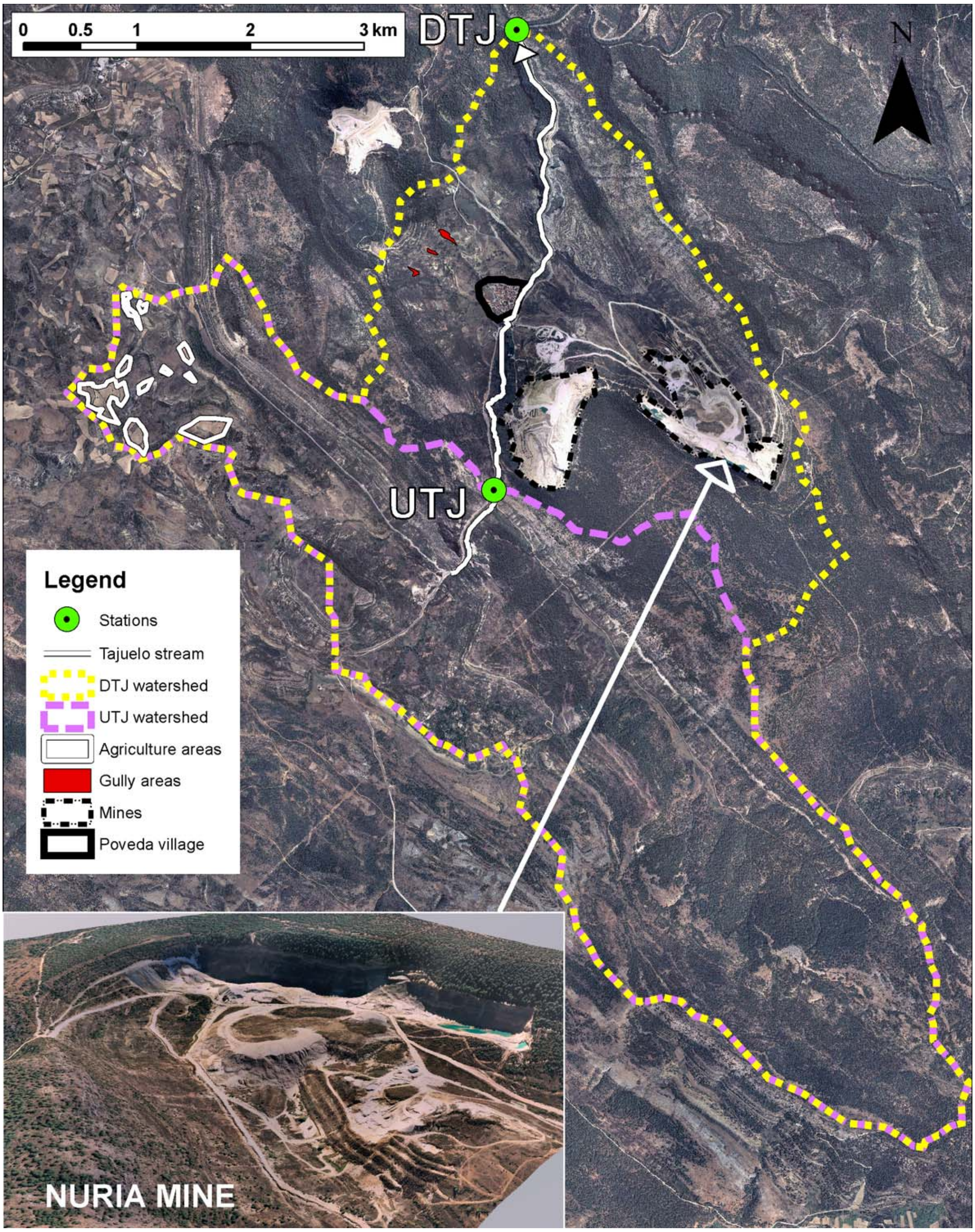

Figure 3.5. The Tajuelo Catchment. Data source: Orthophotograph sheet 539; PNOA 2009: ETRS89.

Table 3.6. The Tajuelo catchment land uses depending on upstream-downstream stations.

land use	UTJ watershed		DTJ watershed	
	km²	%	km²	%
forested and recolonized or reforested abandoned agricultural fields	18.6	98.8	28.71	95.06
mines	0	0	1.17	3.87
village	0	0	0.1	0.33
gully areas	0	0	<0.01	<0.01
agriculture areas	0.22	1.2	0.22	0.73
Total	18.82	100	30.2	100

For example, the Mediterranean Isábena catchment has a badland system representing merely 0.83% of the catchment, but is the likely source responsible for a maximum SSC of 350 g l^{-1} (see Table 3.5). However, the Poveda gullied system is 100 times smaller in its area relative to that of the entire catchment. As relevant, the Isábena badlands are marls producing very high SSCs (Laronne & Shen, 1982; Mathys *et al.*, 2003; López-Tarazón *et al.*, 2009) and fine-sediment loads, whereas the Utrillas sands contribute only low concentrations of suspended sediment and almost all the sedimentary load is transported as sandy bedload (Lucia *et al.,* 2013). The kaolin mines cover 3.87% of the Tajuelo catchment (five times more than the fraction of catchment which the badlands cover in the Isábena Catchment). Due to the extractive activity, materials prone to be eroded – primarily clay-sized kaolin - are exposed and some of these areas are hydrologically connected to the fluvial network. Finally, there are a few active agriculture areas in the west of the Tajo catchment upstream of UTJ. Due to its size (0.73%), it is improbable that these are responsible for SSC values similar to those in the Tajuelo. For instance, in the Enxoé catchment (Ramos *et al.,* 2015), where active agriculture covers at least 87% of the basin, the maximum SSC was 3.5 g l^{-1}. More relevantly, these few agricultural areas cannot explain the very large SSC increase between UTJ and DTJ, because they occur over the entire upper Tajo basin. Hence, the sediment from those agricultural areas is present in UTJ samples, the station used to define the baseline.

SSC baseline for the Tajo and Tajuelo Rivers

This study is based on direct sampling at different river locations. Most of the data derive from baseflow and rising stages and only few from recessions. The number of samples has been sufficient to provide a robust value for low, high and average values of SSC considering that the BACI approach identifies SSC impacts associated with specific local rather than idealized values. Nevertheless, to more fully describe the natural fluvial system and the extent of influence, if any, of the mines on SSC, a fuller sampling program is required. This would best include automatic sampling with continuously measured high-range SSC sensors (López-Tarazón *et al.*, 2009). Furthermore, this study and most others concentrate on suspended sediment, whereas natural landscapes and mines also produce bedload sediments, not to mention a wide gamut of dissolved constituents. Hence, a baseline should ideally be extended to include not merely suspended sediment concentrations but also chemical sampling and analyses (Oyarzun *et al.*, 2011) and bed-material grain size (Saynor *et al.,* 2006).

Another important issue is how to interpret and to apply a baseline database (such as that of Table 3.4), specifically when an impact is being produced and an action or decision is required with respect to the mine areas. The Australian and New Zealand water quality guidelines (WQG) provide some guidance through what they term ‘trigger values’ that, if exceeded, an impact has occurred and an action is required by the authorities. WQG recommend trigger values equal to the 80th, 98th or 99.7th percentiles (e.g., Evans *et al.*, 2004) for each studied parameter. However, no clear explanation is given as to which among these percentiles should be used.

The situation is further complicated by the need that trigger value criteria are agreed by all stakeholders. Thus, defining a reliable baseline and trigger value without knowing the previous conditions with respect to the activity to be evaluated, or other aspects such as the difference in the geological setting within a watershed, is a task with a high degree of uncertainty as shown in Table 3.4. The natural background baseflow values of SSC in the Alto Tajo upstream of the mines are in the range 0.25-0.35 g l^{-1} and should be considered when trigger values have to be adopted, for instance concerning the effects of mines on SSC.

In this respect, the EU Directive 2006/44/EC suggests a maximum concentration of 25 mg l^{-1} for salmonid waters. Although this law states the possibility of no compliance because of exceptional weather or geographical conditions (and this second factor could be applicable here), this concentration has been frequently invoked for this region as a trigger or threshold value. Such an interpretation seems to be very narrow and unrealistic, due to the fact that upstream of mined areas, we measured an SSC baseflow 10 times (0.25-0.35 g l^{-1}) above that level, and an SSC at peak flow 1000 times above this invoked concentration of 25 mg l^{-1}. Summing up, our measurements clarify that the recognition by the EU Directive 2006/44/EC that this parameter can be derogated “because of exceptional weather or special geographical conditions”, and also that “floods are liable to cause particularly high concentrations” may be a pattern rather than an exception. Indeed, it seems more than likely that a similar situation will happen at most sites where direct measurements would be taken. This strengthens the realization that observed values measured continuously in the field are the only meaningful physical values for discussion as SSC baseline, considering its variation with discharge. The clearly insufficient EU Directive 2006/44/EC, and with a narrow interpretation, was used in the Alto Tajo Park until 11 September 2015, when the 817/2015 (BOE, 2015) Spanish law was decreed. This new law does not refer to SSC, merely mentioning hydromorphologic elements that should be monitored bi-annually by using the so-called riparian forest quality index (QBR).

Accurately identifying sediment sources requires continuous monitoring of all the principal sediment sources, both natural (e.g., natural gullies) and anthropogenic (e.g., mine areas). The local authorities in the Alto Tajo Natural Park are attempting to prevent possible mining impacts by fostering two measurements: (i) maintained sediment pond systems for all the active and inactive mining areas; and (ii) replacing traditional restoration methods with others based on reconstructing geomorphically stable surfaces that can manage the discharge, erosion and sediment transport as the natural surfaces surrounding the mines (Martín Duque *et al.*, 2010).

3.5. Conclusions

The local monitoring of the Tajuelo and Tajo rivers in the Alto Tajo Natural Park mining area leads us to conclude as follows: i) This is one of the few locally studies where both an SSC baseline has been defined and the BACI technique have been applied for a mining area; ii) Based on the BACI analysis we conclude that the mined area affects SSC. This effect changes the typical SSC dynamics of a forested catchment with abandoned agriculture to that more similar of badlands; iii) The BACI approach is a simple and reliable method to determine mining, or other human impacts on SSC. It can be used by water authorities or mining companies rather than the all-European 25 mg l^{-1} suggested standard; iv) Determining the precise contribution of the different sediment sources to this change in SSC is complex, because the sources, and the influence of the different geological setting between the upper and lower part of the watershed are manifold and should also be evaluated. Hence, monitoring should be extended toward each source. Moreover, water quality as well as bedload transport should be studied, because they can also be affected by mining.

Acknowledgements

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Capítulo 4

Geomorphic Reclamation for reestablishment of landform stability at a watershed scale in mined sites: the Alto Tajo Natural Park, Spain

Geomorphic Reclamation for reestablishment of landform stability at a watershed scale in mined sites: the Alto Tajo Natural Park, Spain

Abstract

This chapter describes a geomorphic-based mining reclamation process carried out, at a demonstrative level, at the El Machorro mine (Alto Tajo Natural Park, East Central Spain). Specifically, we have used the GeoFluv method implemented by the Carlson Natural Regrade software to design and build a second order stream watershed as a reclamation alternative to the dominant conventional approach of gradient terraces. The process of geomorphic reclamation included: (i) finding suitable and stable landform analogues, and acquiring inputs from them; (ii) designing the watershed, considering local conditions and constraints; (iii) building the planned landscape as designed; and (iv) monitoring the hydrological and erosive – sedimentary response of this watershed. This entire process, from design to construction and monitoring is, in itself, a contribution, due to its scarcity worldwide. The hypothesis is that the new restored watershed will reestablish a hydrological and erosive – sedimentary functionality (dynamics) with landform stability. The runoff, erosion and sediment yield from this reclaimed watershed were monitored during 2012-2016. Erosion and sediment yield were studied from DEM comparisons obtained by Total Station, TLS and topographic reconstruction. A monitoring station with an H-flume, and turbidity and water pressure sensors, allowed quantifying runoff and suspended sediment yield. Until 2015 the sediment yield values were high, due to the lack of a stable local base level for this period, caused by a deficiency in

the building process. In 2014 this local base level was stabilized. From 2015 the magnitude of sediment yield was 18.4 Mg ha^{-1} yr^{-1}, considered to be representative of the current geomorphic dynamics in the reclaimed mine area. This value is only slightly above that (≈ 12 Mg ha^{-1} yr^{-1}) considered to be of tolerable erosion rates. It is also in the lower range (40-12 Mg ha^{-1} yr^{-1}) established by the Queensland Department of Mines and Energy.

Keywords: geomorphic reclamation, mining reclamation, watershed, GeoFluv, Alto Tajo Natural Park

4.1. Introduction

Opencast mining impacts all ecosystem components: substrata, topography, surface hydrology and groundwater, soil, vegetation, fauna, atmosphere and landscape (Nicolau, 2003; Mossa & James, 2013; Martín Duque *et al.*, 2015; Soulard *et al.*, 2015; Tarolli & Sofia, 2016). Those are on-site effects. Mining activities can also have downstream off-site effects, which actually can be more detrimental to the environment. Among these, the impact on water quality associated with high sediment loads discharged from mines to the fluvial system is one of the most harmful ones (Martín-Moreno *et al.*, 2016; McIntyre *et al.*, 2016; Messina & Biggs, 2016; Zapico *et al.*, 2017).

Mining reclamation and rehabilitation is expected to prevent both on-site and off-site impacts. Nonetheless, failures have been common in this regard, in spite of the significant development of mining reclamation techniques during the last decades. The reason is that common mining reclamation techniques have been more 'cosmetic' than functional (Haigh, 2000) and have not been able to guarantee long-term landform stability of reclaimed areas.

To achieve effective control of erosion and sedimentation in mining reclaimed areas and their surroundings, an integrated management of spoils, topography, surface soil cover and vegetation is required (Nicolau, 2003). But, traditionally, geomorphic reconstruction has been broadly relegated in detriment of factors such as soil and vegetation (Nicolau, 2003). Thus, the most common approach of landform management consists of terraced landforms, graded spoil banks comprising alternating short constant-gradient outslopes and benches. But without maintenance, many terraced landforms succumb to water erosion (Loch, 1997). Linear slopes are unstable due to lack or inappropriate drainage density. A study of 57 reclaimed mines in North America illustrated that deficient drainage design was a common reason for failure of mine reclamation landscapes (McKenna & Dawson, 1997). Also because of base level changes, for instance by ditch incision causing the slopes to respond by eroding or mass failure (e.g. Haigh, 1980, 1985). Erosion problems also arise because of ponding or exceeding the storage capacity of the benches (Sawatsky *et al.*, 2000).

Alternatively, another landform approach to mining reclamation, based on designs that replicate `natural' landforms and landscapes, is growing nowadays (Riley, 1995; Bugosh, 2000; Simon-Coinçon *et al.,* 2003; Schor & Gray, 2007; Martín Duque *et al.,* 2010). This approach can be generically called Geomorphic Reclamation, which according to the Office of Surface Mining Reclamation and Enforcement of the United States allows designing *"stable landforms and streams that mimic both the look and the functionality of nature".* Within this approach *"steep rock lined ditches are replaced by meandering streams and uniform or terraced hillsides are replaced by slopes that look natural yet are specifically designed to efficiently convey water without excessive erosion or sediment* *loading"* (OSMRE, 2016). Geomorphic Reclamation is based on the scientific knowledge of geomorphic processes, mostly slope and fluvial ones operating for an extended time within watersheds - the most common landscape organization at the earth's surface.

To the best of our knowledge, there are just a few methods with procedures for replicating natural landforms at sites disturbed by earth movements. The Talus Royal method has been successfully applied at rock roadcuts in France (Génie Géologique, 2016). The Rosgen (1994, 1996) approach has been widely used for stream restoration in the United States, including mined sites. The GeoFluv method (Bugosh, 2000, 2003) has been used for mining reclamation in the US too (see Bugosh *et al.*, 2016). There are also very few software allowing Computer Aided Designs of complex landforms that replicate the natural ones. RIVERMorph (2016) is based on the principles established by Rosgen (1994, 1996) and Natural Regrade is the computerized implementation of the GeoFluv method. RIVERMorph focuses on streams and GeoFluv-Natural Regrade focuses on reconstructing functional watersheds with low order streams. The latter is the geomorphic method and software that better fit with the physiographic conditions of the Alto Tajo mines. Its use will allow testing the landform stability restoration of balanced erosive-sedimentary dynamics at a watershed scale in the surroundings of the Alto Tajo Natural Park, Spain.

GeoFluv is a slope-fluvial geomorphic method to land reclamation allowing the design of landforms, which naturally would erode under the climatic and physiographic conditions at the site. For that, a suitable and stable reference area has to be found for replication. The resulting slopes and stream channels are expected to have long-term stability because they are in balance with the local environment. Natural Regrade is a software that allows users to make GeoFluv designs in a CAD format (Bugosh, 2000, 2003).

In addition, there are also a bountiful set of methods, models and software to evaluate the hydrological, erosive and geomorphic stability, or evolution, of both conventional and geomorphic reclamation methods and their corresponding CAD topographies at mine sites. One way of validating the stability of mining reclamations is by using common erosion models such as RUSLE (Evans, 2000) or WEPP (West & Walli, 1999). The assessment of the most likely long-term topographic evolution of post-mining landscapes by Landscape Evolution Models (LEM), such as SIBERIA or CAESAR-Lisflood, is a key part of the evaluation of mining rehabilitation practices (Willgoose & Riley, 1998; Evans *et al.*, 2000; Hancock *et al.*, 2000; 2002, 2008, 2017). These models can offer good results with a proper calibration (Hancock *et al.*, 2016a), and can also be complemented by direct, field erosion measurements.

Howard *et al.* (2011) have made a revision of different alternative approaches to landform design. However, only very few validating studies on the performance of different types of landforms in mining reclamation have been carried out based on direct field erosion measurements. Of them, it is key to underline that most of them correspond with plots at a slope scale (Merino-Martín *et al*., 2012; Lowry *et al.*, 2014; Martín-Moreno *et al.*, 2016). However, measuring erosion from such plots does not represent the complexity of the behavior and landform stability of a full reclaimed watershed. (Fig. 4.1). An example of such an approach is the watershed monitoring of the GeoFluv geomorphic reclamation of La Plata Mine (Bugosh & Epp, 2014).

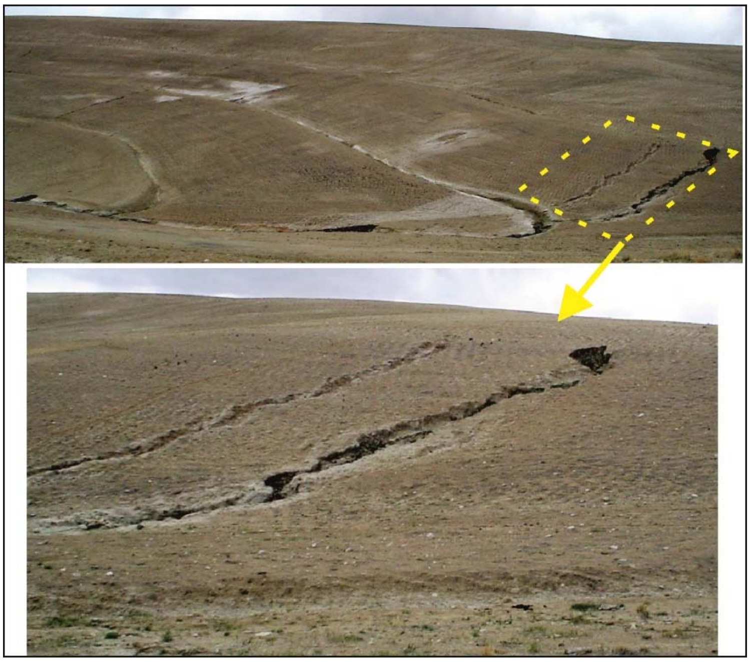

Figure 4.1. Gully erosion of graded terraces at Gas Hills uranium district in Wyoming (US). Photo by Harold Hutson. A study to measure erosion at this site with slope plots, located away from areas affected by gullying, would not reflect the actual erosion of the watershed nor the performance of the reclamation method.

Surrounding the Alto Tajo Natural Park (ATNP) there are several kaolin mines that supposedly increase the sediment yield to the fluvial network. The increase in Suspended Sediment Concentration (SSC) in one the streams crossing a complex mined area inside the park has been measured (Zapico *et al.*, 2017). Due to the high erosive vulnerability of this valued ecological area, the mining company CAOBAR is carrying out geomorphic reclamations based on GeoFluv-Natural Regrade since 2012, with the aim of restoring landform stability and balanced erosive-sedimentary dynamics. This study portraits one of them, located at one of its mined sites, El Machorro.

Spanish laws do not require geomorphic-based mining reclamation, as do the State of New Mexico, United States (NMMMD, 2010). But the most advanced countries with respect to mining reclamation consider nowadays geomorphic principles. For example, Hancock *et al*. (2016b) describe an Australian mine that operates under a set of specific Environment Requirements that are some of the most stringent in Australia, which stipulate that following mine closure, a new landform will be constructed which will need to resemble the surrounding undisturbed landscape. Further, the rehabilitated landform should have erosion characteristics similar to the surrounding environment (Supervising Scientist Division, 1999).

Given the provided introductory framework, the principal aims of this study are: (i) describe the fluvial geomorphic-based mining reclamation at El Machorro with GeoFluv-Natural Regrade; and (ii) evaluate the landform stability of this fluvial geomorphic reclamation, in an active mine, through the monitoring of its hydrologic and erosive response at a watershed scale. Our hypothesis is that, by means of a GeoFluv-Natural Regrade reclamation, we are going to create stable landforms with lower sediment yield, thereby preventing increase of runoff impacts.

4.2. Materials and methods

Study Area

Alto Tajo Natural Park (ATNP) and mining area

Several kaolin mines are located surrounding the ATNP in East-Central Spain (Fig. 4.2). This area is characterized by plateaus and mesas capped by Cretaceous carbonate rocks (limestones and dolostones) underlain by sandy sediments that contain the kaolin (Arenas de Utrillas Formation). From this plateau, the Tajo River has incised a canyon system longer than 100 km and up to 400 m in depth (Carcavilla *et al.*, 2011).

The most common soils draping this landscape are calcaric cambisols, mollic leptosols and rendzic leptosols on top of the mesas, and calcaric cambisols on carbonate colluvia on the slopes (IUSS Working Group WRB, 2007). The vegetation is dominated by *Juniperus thurifera*, *Pinus nigra* subsp. *salzmanii* and *Quercus faginea* (MARM, 1997–2006).

The climate is temperate Mediterranean with dry and mild summers (Csb, according to Köppen, 1918) and with a continental influence. Mean annual precipitation is 783 mm and mean annual temperature is 10 °C (AEMET, 2013). Seasonally, this area is characterized by long and cold winters with snow being common, as well as with short and dry summers. The spring and fall are usually wet. The rainfall erosivity factor, R (equivalent to the R factor of RUSLE), is estimated to be about 800 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988).

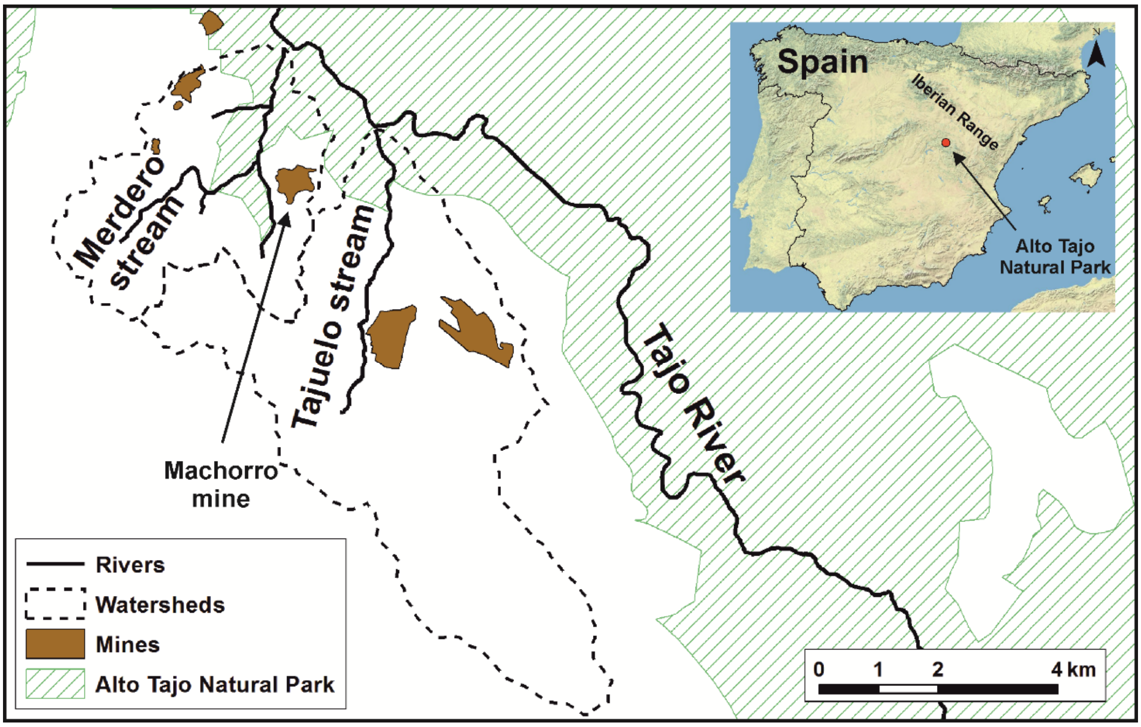

Figure 4.2. Location of the mined areas at the edge of the Alto Tajo Natural Park.

El Machorro mine

El Machorro is one of several active mines in the Alto Tajo area, belonging to the CAOBAR company. It is located in the Merdero watershed (see Fig. 4.2). From this mine, and a nearby one, about 60% of the best-quality production of kaolin of Spain is benefited (Lázaro Sánchez, pers. comm.). El Machorro is a slope quarry which exploitation method is called contour mining. An unpublished report of 1983 (ADARO, 1983) includes a photograph of the mesa-type hill where El Machorro mining began in the year 2000 (Fig. 4.3).

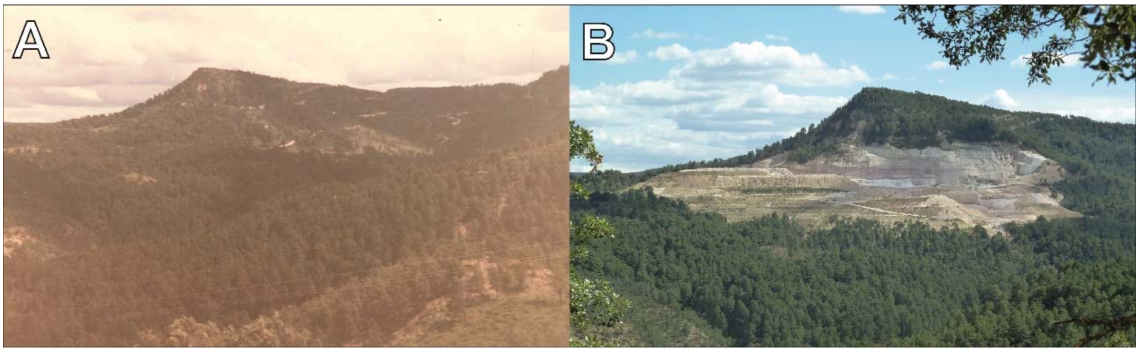

Figure 4.3. A: Pre-mine landscape of El Machorro (ADARO, 1983); small mesa-type, its slopes and surrounding valleys supporting a pine forest. B: El Machorro mine in 12.09.2013.

One of the most interesting scientific and applied aspects of this mine is that it has undergone up to four different generations or approaches of mine reclamation (Fig. 4.4). As an active mine, a large part of its surface is either dynamic open pit (a) or waste dumps (b). A system of ponds (c) control the runoff and sediment yield from these active areas. Both runoff and sediment mostly derive from un-reclaimed waste dumps, which are subject to high runoff and active erosion, both in the form of rills and gullies (Fig. 4.5). The areas which are not active open pit or waste dumps have been rehabilitated, displaying different approaches (or "generations") of mining reclamation, from conventional to geomorphic ones: (R1) terraces (linear outslopes – benches systems) covered with carbonate colluvium with hydroseeding and planted pines; (R2) smoothed sloping terraces covered with carbonate colluvium; (R3) terraces (linear outslopes – bench systems) covered both with carbonate colluvium and soils, without hydroseeding; and (R4) geomorphic reclamation by using GeoFluv-Natural Regrade (site of the study described in this chapter).

Figure 4.4. Oblique aerial view of the El Machorro mine in 2014. Letters are explained in the text. Photo by Paisajes Españoles (2014). See text for a more detailed explanation.

This mine also has an experimental mining reclamation waste dump (ER), in which the sediment yield from a combination of two morphologies (terraced and concave) and two soil covers (carbonate colluvium and original soils) was measured during two years (Martín-Moreno *et al.*, 2016) They were used to improve the traditional reclamation at this mine, by properly rescuing original soils and by modifying the terraced topography to concave ones. In this framework, it is key to consider that concave slopes are an improvement relative to linear slopes (Martín-Duque *et al.*, 2010), and that concave slopes extend with and into drainage networks in Nature. This is where fluvial geomorphic reclamation by GeoFluv – Natural Regrade completes the sequence, reclaiming watersheds with a drainage network having functional channels "stitched" with convex – concave slopes.

Figure 4.5. Erosive-sedimentary landforms of spoil heaps inside the El Machorro mine. A: rills and associated sand cones; B: gullies and sand sheets with miniature braided landforms.

Fig. 4.6 shows the monitored geomorphically reclaimed area by using GeoFluv-Natural Regrade. It was restored in two phases, one in 2012 (2012GF, 0.65 ha) and a second in 2014 (2014GF, 0.41 ha).

Geomorphic design and construction using GeoFluv

GeoFluv™ is the trademark name for a specific, patented method of landform design. It uses algorithms based on slope and fluvial geomorphic principles. The essence of this approach is to identify the type of drainage network that would tend to form over a long time at a given location, i.e., to achieve a dynamically quasi-stable landform, considering the site's earth materials, relief and climate. This is identified at a suitable landscape reference, in which specific measures (such as drainage density or maximum distance from ridgeline to channel head), are made. These are used for designing the site (Bugosh, 2000, 2003). The resulting slopes and stream channels are stable because they replicate geomorphically-mature landforms that have natural stability.

Figure 4.6. Oblique aerial view of the El Machoro geomorphic reclamation site. 2012GF: geomorphic reclamation constructed in September 2012 and 2014GF in September 2014. Photo by DGDRONE (2015).

A typical GeoFluv-Natural Regrade geomorphic reclamation process includes the following steps: (1) define the local environmental conditions and locate stable natural landforms similar to the mine wastes to be reclaimed, within similar environmental conditions to those of the project area (climate, soils and vegetation), thereafter measure their characteristic features (field inputs); (2) set the design area and its topographic conditions in CAD; (3) make a geomorphic reclamation design following GeoFluv - Natural Regrade, and validate its stability and correct performance; (4) obtain the topographic information for automatic machine control, or for topographic survey staking out; (5) build the designed landforms; and (6) monitor the hydrological and erosive-sedimentary response of the geomorphic reclamation (Fig. 4.7).

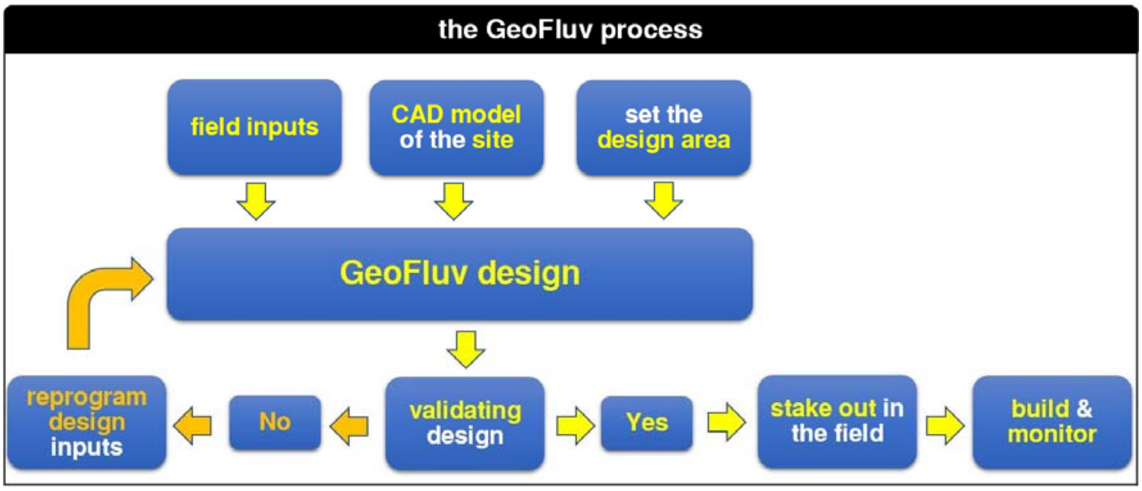

Figure 4.7. Diagram showing a typical GeoFluv procedure. Redrawn from: http://www.landforma.com/about-geofluv/.

Monitoring of the geomorphically reclaimed area

The geomorphic-based reclaimed area has been monitored to determine its stability and response. This has been achieved by means of different methods and for different periods and zones (Table 4.1).

Table 4.1. Methods and dates of the monitoring of the geomorphic reclamation area in the El Machorro mine.

initial date	final date	area studied	method	target parameter
2012 September 2014 September	2015 April 2015 April	2012GF 2014GF	comparison between one topography scanned and another reconstructed (interpreted)	total sediment yield
2015 April	2016 July	2012GF and 2014GF	surface comparison between two scanned topographies at the whole area	
2013 September 2015 April	2014 February 2016 July	2012GF 2012GF and 2014GF	surface comparison between two scanned topographies at an outlet pond	
2014 September	2016 July	2012GF	suspended sediment concentration (SSC) station	suspended sediment load

Erosion-Total sediment yield

Erosion and sediment yield were obtained by the comparison of topographies measured at: (i) the geomorphically reclaimed area; and (ii) a pond located at the outlet of the reclaimed area, which stored all the sediment yield (Fig. 4.8).

Topographies were surveyed by different methods: differential GPS, Terrestrial Laser Scanner (TLS) and topographic reconstruction (Table 4.2).

The pond, which was dug in natural land on silica sand bedrock, was constructed in September 2013. It was monitored during two periods surveying the topography after and before the period. During the first one, it was totally filled by sediment and it was emptied before the second monitored period. The pond totally lost its efficiency of retaining sediment when it was totally filled by sediment. In addition, when the pond was not filled, there is evidence that during the larger runoff events, water flowed out of the pond. This water must have carried out some suspended sediment. Although some of the sediment was not retained by the pond in those events, field evidences also showed that such spilling events were rare, and we therefore assume that this circumstance does not significantly affect the obtained value.

Table 4.2. Summary of the different methods used to obtain the topographies; p, pond; s, surface.

code	area	date	survey method	accuracy (m)
2013p	outlet pond	2013 September	differential GPS	0.023
2014p		2014 February	TLS	
2015p		2015 April	TLS	
2016p		2016 July	TLS	
2012s	2012GF	2012 September	topographic reconstruction	0.033
2014s	2014GF	2014 September	topographic reconstruction	
2015s	2012GF and 2014GF	2015 April	TLS	
2016s		2016 July	TLS	

The first survey of the pond (17.09.2013) was obtained with Leica's differential GPS 1200. For this instrument, we assume an accuracy of 2.3 cm (Brasington *et al.*, 2003).

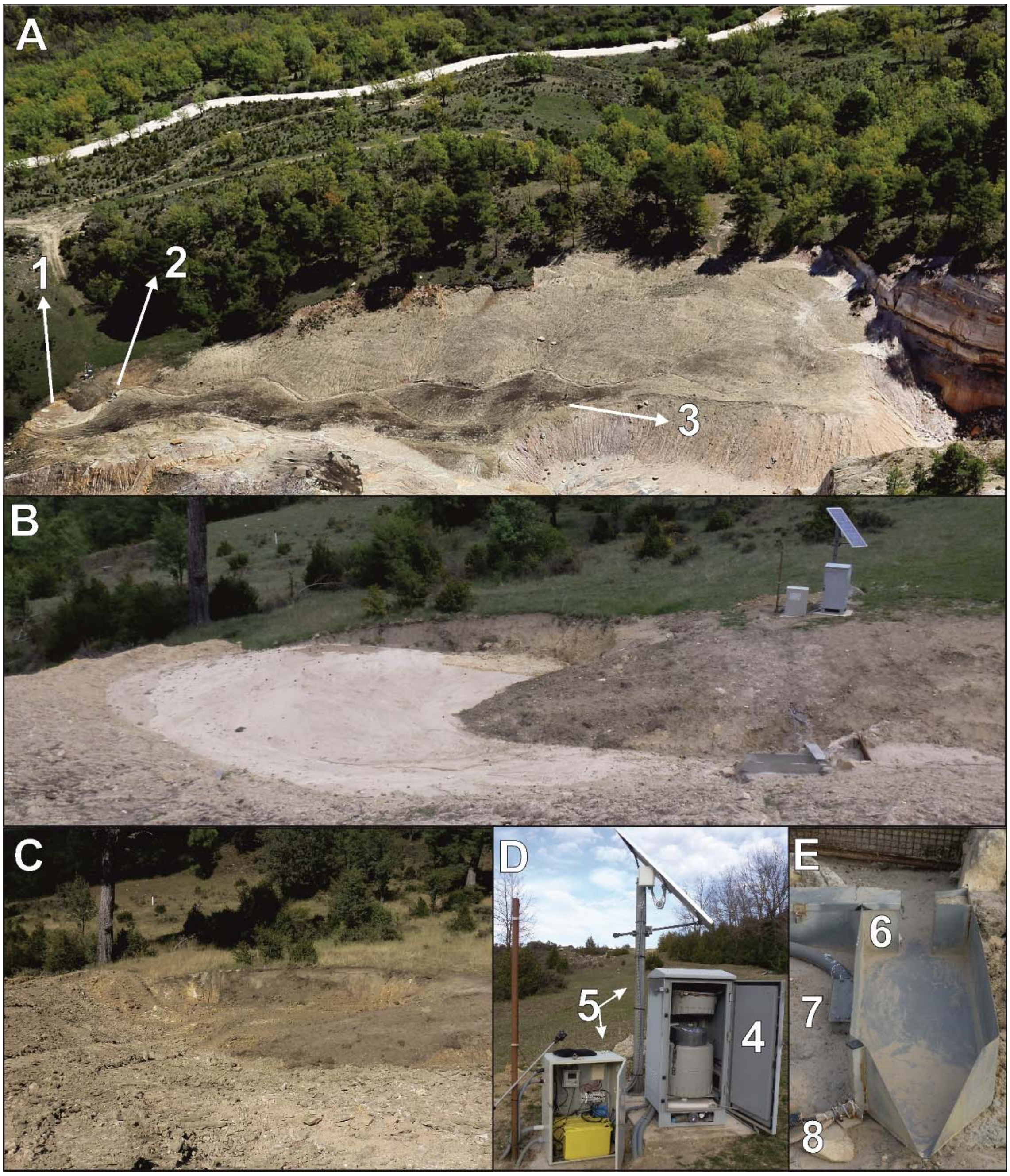

Figure 4.8. Sediment monitoring at El Machorro geomorphically reclaimedsite. A: oblique aerial view of the 2012GF area (1: pond; 2: SSC station; 3: rain gauge). B: view of the filled pond and the SSC station. C: view of the empty pond. D and E views of the SSC station (4, ISCO sampler; 5, solar panel, batteries, datalogger and telemetry; 6, turbidimeter; 7, strainer that takes the samples; 8, pressure sensor).

Five of the topographies (two from the entire reclaimed area and three of the pond) were obtained as point clouds using an M60 MultiStation (Leica), having both Total Station and TLS capacities. Before processing the point clouds, each one was cleaned to remove non-ground elements in the topography, such as vegetation or 'noise', using the LP360 Advanced edition software (Qcoherent, 2015).

During the last topography-driven field campaign (11.07.2016) we also surveyed some control points, independent points measured with the total station function of the MS60. These were not used to georeference the point clouds, and the root-mean-square error (RMSE) was calculated to evaluate accuracy with the LP360 control point tool following the American Society for Photogrammetry and Remote Sensing (ASPRS) guidelines (ASPRS, 2014). Although the RMSE was calculated only once, every scanning was carried out with the same control points used to georeference the point clouds, and following the same procedure. The accuracy was 3.3 cm.

When the last topographical survey was completed in July 2016, the reclaimed surface had a significantly higher vegetation cover in contrast with that in April 2015 (see Fig. 4.9). We therefore proceeded to 'clean' those areas having vegetation clumps, producing a surface entity in which several polygons appeared without points (see Fig. 4.9-B.1 and 4.9-B.2). Besides, the cleaned point cloud for July 2016 (Fig. 4.9-B.2) had a lower data density than that of April 2015 (Fig. 4.9-B.3), even though they were surveyed following the same procedure. The reason for the difference is that vegetation acted as a 'screen' for the scanning process, making a shadow effect for the point gathering. The removal of vegetation has been used in similar studies, in which vegetation also interfered with topography (Smith & Vericat, 2015). Indeed, dealing with vegetation is a demanding task in topographies surveyed with TLS compared with other methods, such as ground-based GPS and total station (Wheaton *et al.*, 2010). With this decision, we assumed that areas with vegetation had no significant erosion, and that erosion occurred in areas with lack or low vegetation cover. This was confirmed by field evidence (small landforms of erosion, such as rills, appeared in areas without vegetation, and lacking signs of mass wasting). However, rainsplash, or sheet-overland are possible erosion mechanisms in these areas, which could not be measured.

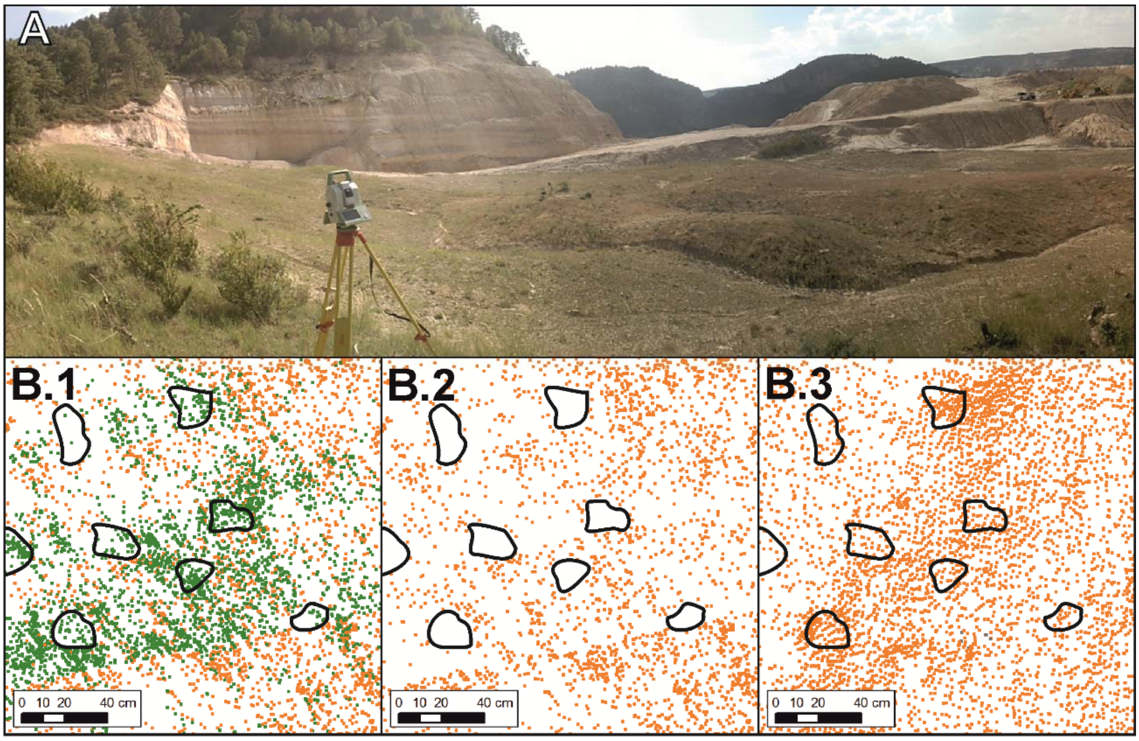

Figure 4.9. A. View of the scanned area in July 2016. Notice the vegetation cover. B: Details of the 'vegetation effect' for topographic comparison (vegetation-green; ground-orange). B.1., 2D point cloud of the reclaimed area in the last scanning (July 2016), with all the scanned points. B.2., situation as of July 2016 only with ground points. B.3., situation in April 2015 with all point scanned and absence of vegetation.

To obtain the initial topography of September 2012 and of September 2014 we reconstructed these initial stages from the topography data of the first scanning in 2015. A similar approach was used in equivalent research situations (Martín-Moreno *et al.*, 2014; Martín Duque *et al.*, 2015). First, from the point cloud of 2015 we derived a 0.2 m equidistant contour shapefile. The erosion between 2012-2015 (for the 2012GF area) and between 2014-2015 (for the 2014GF area) occurred mostly as an incision in the main channel, and as rilling in the swales

(Fig. 4.10). Therefore, we smoothed the contours in those areas until they reflected the presumed initial topography (Fig. 4.10). Because the resultant topography is derived from another measured by TLS, we assumed both the same accuracy of 3.3 cm. However, it is not possible to define the accuracy of the reconstruction process.

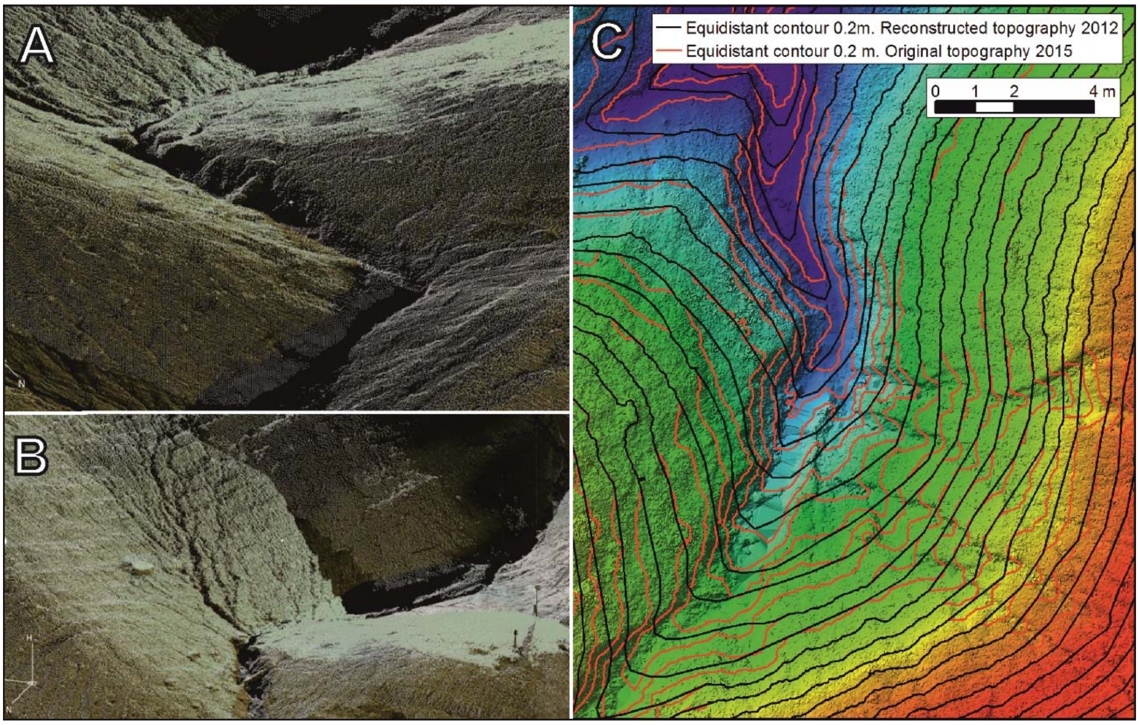

Figure 4.10. Details of the erosive landforms appearing in the 2012GF area. A: point cloud view reflecting the incision in the main channel. B: point cloud view reflecting the rilling in the swales. C: in red, 0.2 m equidistant contour from the scanned topography in April 2015; in black, 0.2 m equidistant contours reconstructed to simulate the September 2012 topographic conditions. Both contours are overlaid to a TIN file obtained from the point cloud scanned in April 2015.

A Digital Elevation Model (DEM) was derived from each topography. Depending on comparison needs (see Table 4.1), respective DEM of Differences (DoDs) were obtained by using the Geomorphic Change Detection (GCD) software (GCD, 2015), which allowed quantifying the topographic change between two dates. Specifically, each DoD represents the total net volume eroded or deposited for that period. The methodology of GCD software (Wheaton *et al.*, 2010) is based on establishing a minimum level of detection ($_{min}$LoD) defined by the accuracy of each topography. It is assumed that DoD changes below these values cannot be detected and have to be removed from the volume analysis. Errors were also calculated (Brasington *et al.*, 2000). Once the volume was obtained, the mass of sediment (Mg) was calculated by multiplying it by the sediment bulk density (1.2 g cm^{-3}). The bulk density had been previously calculated for these same materials (see Martín-Moreno *et al*., 2016) using the core method (Blake, 1965). Additionally, an image of each DoD was obtained, showing the areas where erosion or deposition occurred.

Runoff and Suspended Sediment Concentration (SSC)

An SSC monitoring station was installed to continuously record SSC (turbidity of the runoff; Fig. 4.8) upstream of the outlet pond and downstream of the 2012GF reclaimed area. This station had:

(i) An 0.229 m H-flume (Teledyne Isco, 2008) through which all the runoff produced at the reclaimed area passed;

(ii) A 720 Submerged Probe Module (ISCO) to measure water depth every 5 minutes (variations from 1 to 10 min were made until tests demonstrated the best lapse of time). Water discharge (Q) was derived from the records of water depth in the flume. This sensor was also used to obtain an SSC-discharge equation, which allowed calculation of SSC for periods when the turbidity sensor had no record. This sensor was operational during 01.07.2014 to 01.04.2016 and was calibrated with 41 samples (ranging among 4 and 45 g l^{-1}) taken by an ISCO sampler. The rating curve is SSC (g l^{-1}) = 7880.5*Q (m^3 s^{-1})+5.7109 (r^2=0.6).

(iii) Automatic 24 bottles ISCO 6780 portable sampler. Water and sediment that flowed through the flume was pumped by a suction line connected to the ISCO sampler and to a strainer inside the flume. The sampler was triggered by the 720 Module when water depth attained 5 cm. This means that when the strainer was entirely covered by water, this situation was detected in the flume, in which case samplers were taken each 1 minute.

(iv) A ViSolid 700 IQ Suspended Solids Sensor (0-300 g l^{-1}) connected to an IQ SensorNet 182 controller (WTW), measuring data each 1 minute. The Total Suspended Solids Sensor was calibrated with 6 samples (4 and 45 g l^{-1}) taken by the ISCO sampler through a rating curve such as is common (e.g., López-Tarazón *et al.*, 2009). The statistically significant rating curve is SSC (g l^{-1}) = 0.9586*($SSC_{turbidimeter}$ (g l^{-1})) - 0.1008 (r^2=0.74). This device was in operation between 04.05.2015 to 01.04.2016.

(v) One tipping-bucket rain recorder (Davis *Rain Collector II*) to measure rainfall.

Because the reclaimed area produced a higher-than-expected amount of bedload, which initially covered these instruments, a 2 mm mesh sieve was installed upstream of the flume. This sieve retained the bedload, but allowed the finer grained suspended sediments to pass through. After each event, or a series of consecutive events, the sediment trapped by the mesh sieve was cleaned, and downloaded in the pond (so that it could be measured). Simultaneously, the sensors were cleaned and the pressure sensor was recalibrated when needed.

Data from all the sensors were downloaded by means of a telemetry and an alarm system, which allowed knowledge in real time when an event was occurring, the amount and intensity of each rainfall event, as well as the number of bottles filled by the ISCO sampler.

4.3. Results

Geomorphic reference and derived design inputs

The analogue of stable landforms naturally developed on geologic materials similar to those of the spoils of El Machorro, and also in similar environmental (climate) conditions to be used at the geomorphic design with GeoFluv-Natural Regrade, was found within the municipality of Peñalén, at a location of about 3750 m east of the mine (Fig. 4.11). The geomorphic stability of the area was determined by the absence of landforms denoting erosion or mass movement activity (such as rilling, gullying, knickpoints or terracettes).

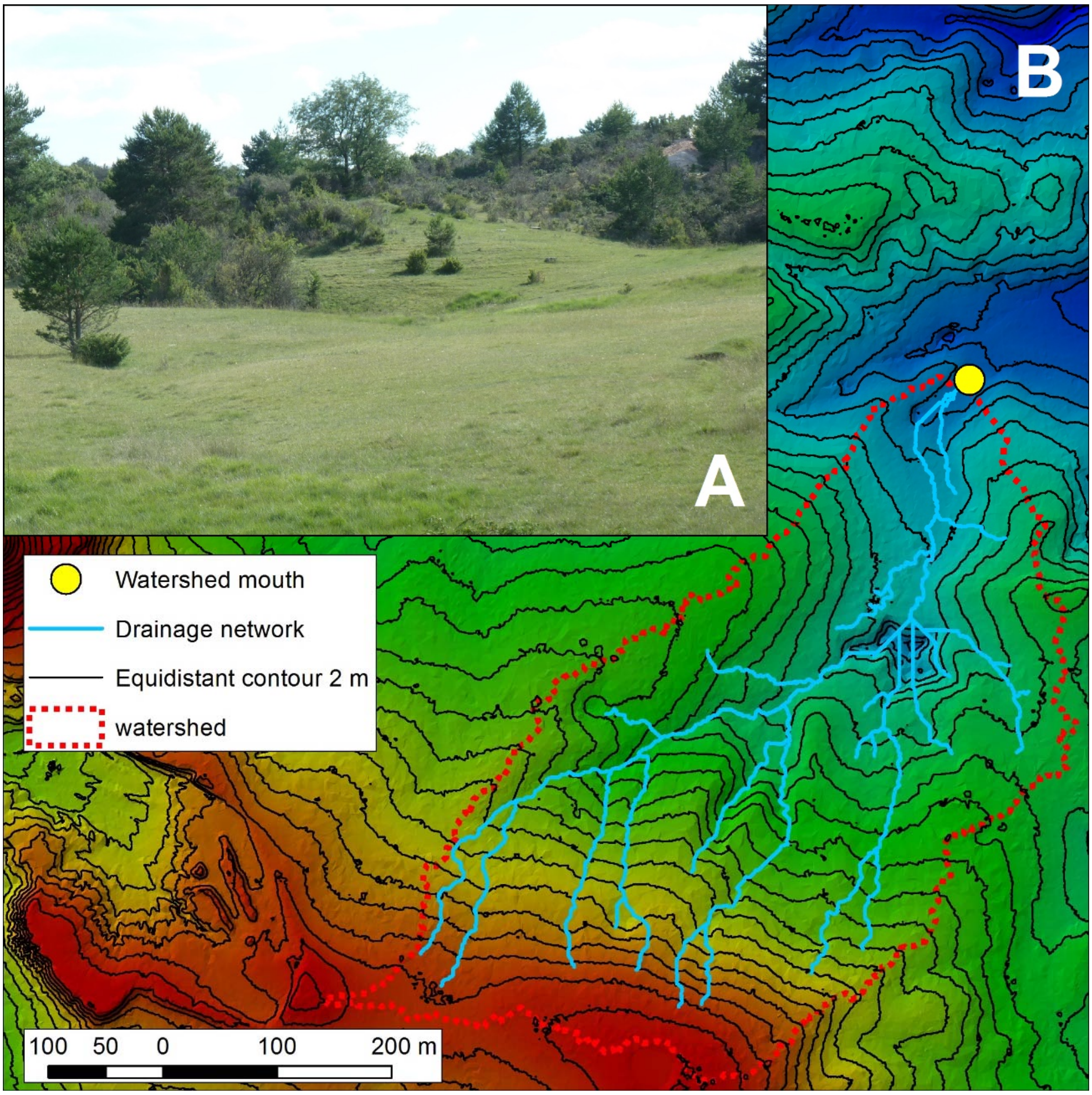

Figure 4.11. Reference area used for designing the geomorphic reclamation of the El Machorro: A) ground photo of the area; B) map of one of the watersheds used to obtain inputs, with the drainage network overlaid to a TIN file obtained from the point cloud of PNOA (2009).

GeoFluv – Natural Regrade uses three types of settings (Table 4.3). The first group are those based on the needed adjustments to the local topographic conditions at the site to be reclaimed. One of these settings is, for example, the local base level, slope at the mouth of the lower channel in the main valley, in this case entering the outlet pond. A second group corresponds to morphometric parameters of the suitable local stable reference landscape (Fig. 4.11). Finally, precipitation data corresponding to values which are associated with bankfull and flood prone discharge are needed.

Table 4.3. Inputs used for the geomorphic design of El Machorro by using GeoFluv-Natural Regrade.

nº	input/settings and units	Units	method/reference	value
Topographic conditions of the design area				
1	slope at the mouth of the main valley bottom channel	%	local base level measured at the channel that drains the quarry, outside it	4
Morphometric inputs from a stable reference landscape				
2	'A' channel reach (average) - type of channel with slope higher than 0.04, according to Rosgen (1994)	m	field measurement with tape measure	16.6
3	maximum distance from ridgeline to channel's head	m	aerial photo-interpretation and/or hydrology analyses by using high resolution digital elevation model	37
4	target drainage density	m ha^{-1}	analyses with GIS	199
5	sinuosity of channels with slope higher than 0.04	-	ratio of channel length to the length of the 'A' channel belt axis	1.2
Precipitation and hydrological data				
6	2 yr - 1 h precipitation	cm	IDF curves and MAXIN (2008)	2.15
7	50 yr - 6 h precipitation	cm	application	8.92
8	runoff coefficient	-	it is a function of both the spoils and soils. Assigned according to the own experience in similar reclaimed landscapes	0.3

GeoFluv-Natural Regrade landform design and construction

Fig. 4.12A shows the GeoFluv - Natural Regrade output design for El Machorro. It imitates the landforms of the geomorphic natural analogue, with the aim of restoring a similar functionality, and it is adapted to the topographic constraints of this sector of the mine and to the available spoil heap volume, among other local factors. The designed landforms consist of: (a) zig-zag channels, with slope between 4 and 10 %, sinuosity <1.2 and sand material; (b) rounded interfluves, the slopes of which have a 'scalloped' topography, forming sub-watershed ridges and tributary channels (or swales) (c). Along the divides of these ridges, small saddles were also designed (Fig. 4.12A).

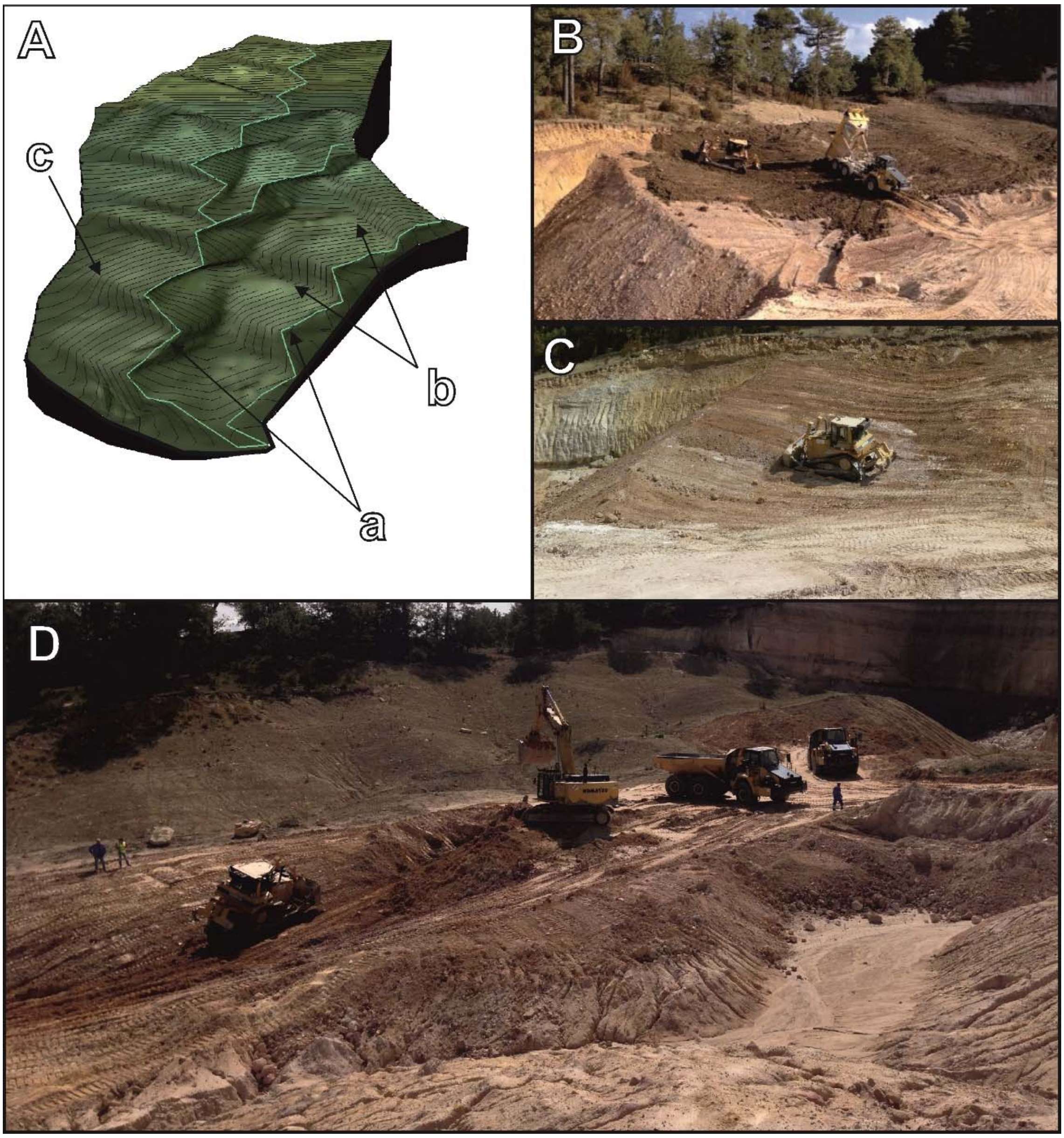

Figure 4.12. Details of the geomorphic design and construction at El Machorro. A, 3D view of the geomorphic design; B, articulated dump trucks and bulldozer spreading top-soil; C, bulldozer building a sub-channel (swale); D, excavator, bulldozer and articulated dump trucks cutting the main channel at 2014GF area.

As stated, this design was constructed in two phases (Fig. 4.6): one in September 2012 (2012GF) and another in September 2014 (2014GF). Spoil mass hauling was carried out by an excavator and two articulated dump trucks. The final regrade of these surfaces, the process that completes the construction of the geomorphic design, was accomplished by a bulldozer. Fig. 4.12B, C and D show the two main processes involved in this type of topographical regrading: building

A-type (zig-zag) channels and the subwatershed ridges and swales on the slopes, resulting in a scalloped topography.

The geomorphic reclamation was completed with soils restoration and re-vegetation. Original soil that was ‘rescued’ in active kaolin exploitation areas was used to spread the topsoil dressing. Soil removed where the exploitation is advancing, was directly loaded in articulated dump trucks, and spread on the geomorphically-reclaimed area.

Afterwards, the area was seeded and planted with suitable herbs, shrubs and trees. At the end of the 2016 summer the vegetation cover was about 30%, in part due to natural dispersion and colonization (Campos, 2016).

The average slope gradient of the constructed channels is 11%. The ridges and sub-channels have and average slope of 31% and 28.1% respectively. Fig. 4.13 shows a comparison of the 2012GF area at the beginning (September 2012) and several months after the geomorphic reclamation (May 2014).

Monitoring of the geomorphic reclamation

Erosion-Total sediment yield

The first scanning of the 2012GF and 2014GF areas was made in April 2015 (Fig. 4.14A) and had a density of 684 points/m^2; after the cleaning process it was reduced to 676 points/m^2. The second scanning (July 2016) had similar densities (686 and 597 respectively). Fig. 4.14B shows the interpretation of the topography (after the process of reconstruction) for these areas immediately after the process of geomorphic reclamation was completed and before erosion had occurred.

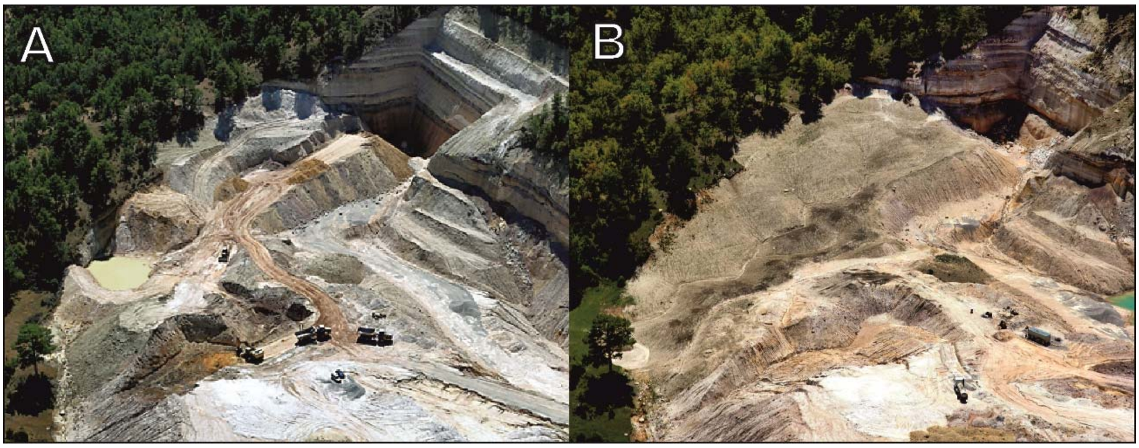

Figure 4.13. Oblique aerial photos of the 2012GF area. A, at the beginning of the geomorphic reclamation, September 2012. B; in May 2014. Photos by Paisajes Españoles.

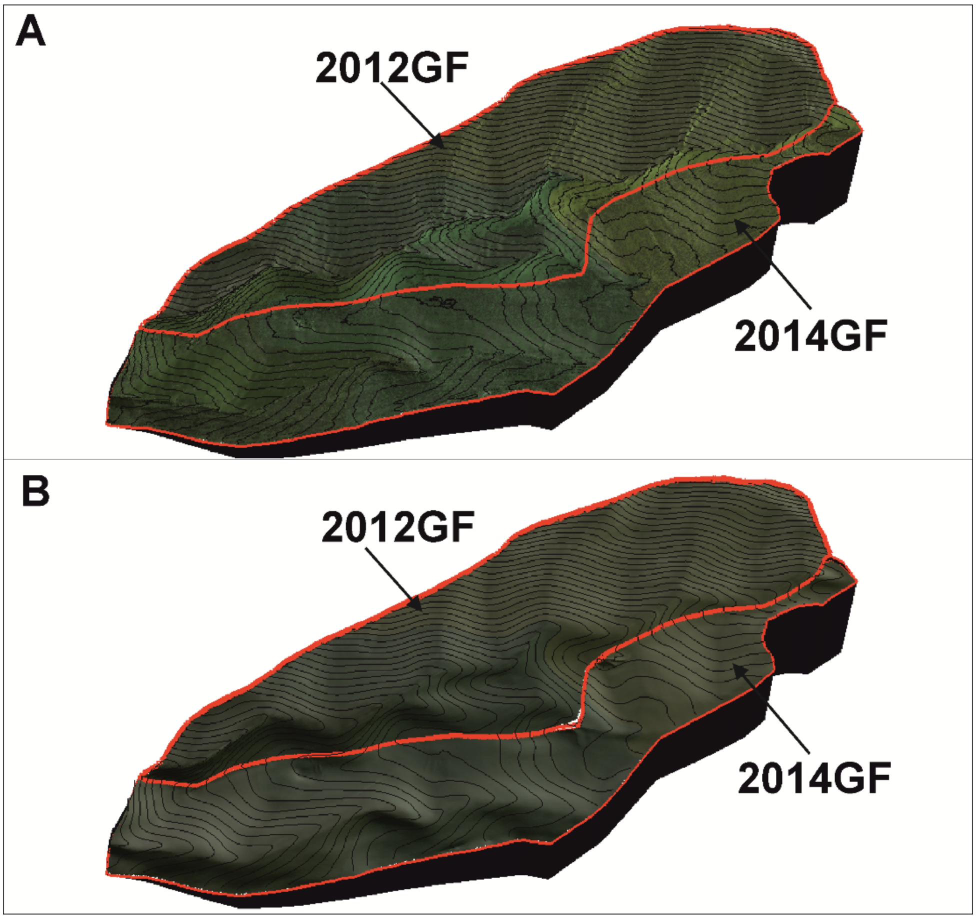

Figure 4.14. A, 3D view of the topography scanned in April 2015 (2012GF and 2014GF areas); B, 3D view of the topographic reconstruction for the same areas after the geomorphic reclamation.

The pond was entirely filled in February 2014 due to erosion occurring during this first monitoring period from September 2013 to February 2014, and only from the 2012GF restored area. We know the data of pond filling because of field reports collected through periodical visits. During the second monitoring period, April 2015 - July 2016, the pond was not totally filled and received sediments from both the 2012GF and 2014GF areas.

Table 4.4 shows all the sediment yield values estimated from the different topographic comparisons, as well as their associated errors. As far as the pond is concerned, the highest value, 95.3 Mg ha^{-1}, from the first monitoring period (September 2013 to February 2014), cannot be extrapolated to yearly rates, because it only reflects erosion from 5 months in an area with contrasted seasons. However, the pond-based value for the second monitoring period can be expressed annually: 18.4 Mg ha^{-1} yr^{-1}, values having the smallest topographic errors. The values obtained from the topographical comparison between DEMs and their initial-reconstructed ones, and from direct DEM comparisons range from 23.1 to 71 Mg ha^{-1} yr^{-1} (Table 4.4).

Table 4.4. Sediment yield values obtained for the geomorphically reclaimed surface from pond sedimentation and from DEM comparisons. nd: No yearly data, because the monitoring period was shorter than a year.

period		source area	sediment yield				total
start	finish		total	error (+/-)	annual	error (+/-)	rainfall
-	-	-	Mg ha^{-1}		Mg ha^{-1} yr^{-1}		mm
direct DEM comparison at sediment pond							
17/09/2013	13/02/2014	2012GF	95.3	7	nd	nd	340
08/04/2015	11/07/2016	2012GF and 2014GF	23	3.6	18.4	3	813
topographical comparison between measured DEM and reconstructed initial surface							
17/09/2012	08/04/2015	2012GF	184	74	71	28	1384
17/09/2014	08/04/2015	2014GF	10.2	29.9	nd	nd	360
direct DEM comparison of the reclaimed surfaces							
08/04/2015	11/07/2016	2012GF	17.3	14.9	27.7	23.8	813
08/04/2015	11/07/2016	2014GF	11.5	11	23.1	22	813

Fig. 4.15 shows the DoD for the geomorphically reclaimed surface and for the outlet pond. At the former, catchment area, erosion has occurred mainly as a moderate incision of the main channels (locally reaching 0.5 m). At the latter, the process has been deposition, with a depocenter of about 1 m.

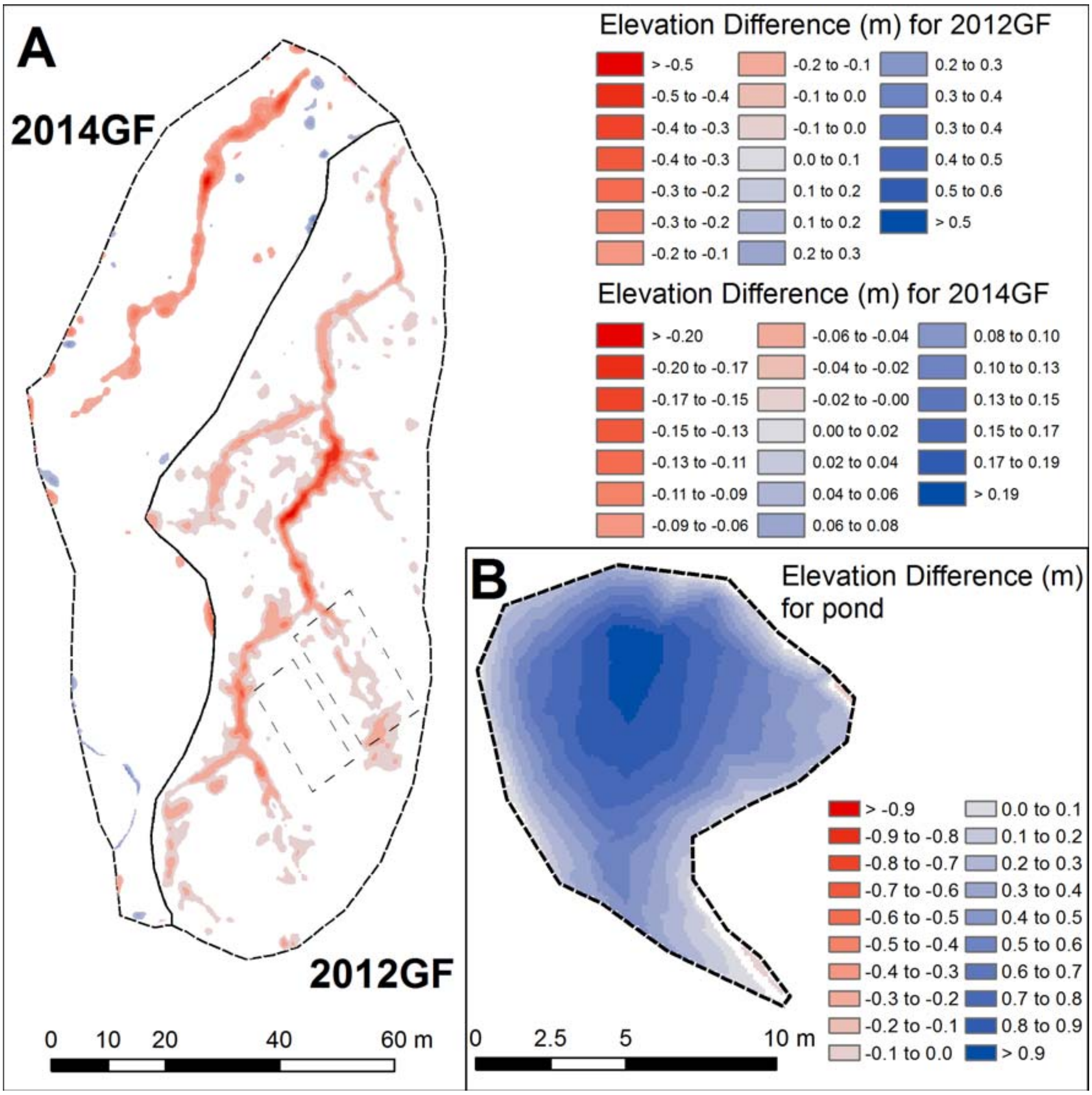

Figure 4.15. DoDs for the El Machorro reclamation area. A: between the April 2015 scanned surface and the reconstructed one; B: pond DoD for the period September 2013 - February 2014. The rectangles in figure A intend to visualize how, had erosion of this area been monitored with slope plots, the difference in erosion between two plots would have been very large because erosion occurs mainly at swales and main the channel.

Runoff, Suspended Sediment Concentration (SSC) and Suspended Sediment Load (SSL)

During the monitoring period we recorded 34 runoff events (Table 4.5). It was not possible to collect data from all the events because of several problems with the sensors: a) power outage due to snow covering the solar panel; b) pressure sensor covered by sediment; and c) temperatures below zero triggered ‘false’ events. Taking into account the Natural Park rangers' field reports and the rain gauge data, we established that rain above 3 mm in 6 hours triggered runoff events. However, events with higher precipitation of 3 mm in 6 hours had no associated runoff data, due to the aforementioned problems. Accordingly, we estimate that the number of events for this period was 66. Hence, we have collected 52% of the runoff events (34/66 in total, being 12/19 in 2014, 14/30 in 2015 and 8/17 in 2016). The mean discharge was 0.6 $l\ s^{-1}$ and the maximum instantaneous discharge was 18 $l\ s^{-1}$. The latter belongs to event #3 in 2014 the highest value of SSC and total SSL with 148 $g\ l^{-1}$ and 3320 kg respectively. In this event, the runoff coefficient was 0.46; and the highest and mean discharge were 18 and 2 $m^3\ s^{-1}$ respectively. The highest runoff coefficient was 0.8 (for event #30) in 2016. However, the corresponding SSC and total SSL values were only 9.9 $g\ l^{-1}$ and 974 kg.

4.4. Discussion

The geomorphic reclamation carried out at the El Machorro Mine intends to be a real alternative to the dominant conventional approach of gradient terraces. Therefore, evaluating its performance in terms of landform stability and hydrological and erosive-sedimentary dynamics, is required.

The sediment yield monitoring of the geomorphically reclaimed area was accomplished by using different methods and instruments due to a variety of reasons (ranging from the availability of topographical instrumentation during the monitoring period to contingencies due to mining activity). Instruments' accuracies required estimation of corresponding errors (Brasington *et al.*, 2003) was calculated. In order to simplify, we split the sediment yield monitoring in two periods: September 2012 - April 2015, and April 2015 - July 2016.

Table 4.5. Water discharge and suspended sediment concentration and load for the monitored events between 01.07.2014 and 01.04.2016.

event	date	Q_{mean}	Q_{peak}	total runoff volume	rainfall volume	runoff coefficient	SSC mean	SSC max	total SSL
		$l\ s^{-1}$		mm		-	$g\ l^{-1}$		kg
1	02.07.2014	1	4	2.6	16.4	0.16	14.3	36.1	403
2	03.07.2014	0.3	1	0.5	12.3	0.04	8.2	15.5	34
3	03.08.2014	2	18	9.3	20.1	0.46	19.2	147.6	3324
4	04.11.2014	1	2	1.7	31.7	0.05	12.7	22.6	176
5	09.11.2014	0.2	0.3	>0.1	4.5	0.01	7.6	7.8	1.1
6	11.11.2014	0.2	0.6	0.2	14.1	0.01	7.4	10.7	9.3
7	15.11.2014	0.1	0.2	>0.1	4.5	0.01	7.1	7.4	1.8
8	27.11.2014	2	4	1	4.1	0.24	18.1	34.7	195
9	28.11.2014	0.7	2	0.9	20.7	0.04	11.1	20.6	88.4
10	30.11.2014	0.1	0.2	>0.1	40.5	0.01	6.8	7.3	1.2
11	01.12.2014	0.2	0.5	0.1	10	0.01	7.6	9.3	4.6
12	14.12.2014	0.1	5	11.4	23.4	0.49	12.9	42.1	1169
13	23.03.2015	0.6	2	1	12	0.08	7.7	13.5	51.6
14	11.06.2015	0.5	1	0.15	6.8	0.02	10	14.1	11.6
15	21.08.2015	0.5	0.5	>0.1	9.2	0.01	24	24	8
16	22.08.2915	0.8	0.8	0.1	2.6	0.03	13.6	13.6	6.7
17	16.09.2015	0.2	0.3	>0.1	7.8	0.01	7.9	9.2	2.2
18	05.10.2015	0.7	2	0.5	4.9	0.1	11.3	20.1	51.5
19	06.10.2015	0.9	9	0.1	3.9	0.02	12.7	12.7	6.8
20	13.10.2015	0.1	0.1	>0.1	4.5	0.01	12.7	12.7	0.8
21	17.10.2015	0.2	0.2	0.5	5	0.1	7	7.5	21.9
22	18.10.2015	0.2	0.3	0.4	1.4	0.28	7	7.8	2.4
23	19.10.2015	0.2	0.3	0.7	3.3	0.2	6.9	7.8	30.9
24	28.10.2015	0.1	0.1	>0.1	3.1	0.02	6.4	6.7	2.5
25	06.11.2015	0.4	6	5.1	29.9	0.17	10.8	50.5	695
26	21.11.2015	0.1	0.1	>0.1	3.3	0.01	6.6	6.7	2.3
27	01.01.2016	0.4	0.7	0.2	10.5	0.02	5.4	6.5	7.8
28	03.01.2016	1	10	7.2	45.5	0.16	7.4	17.3	398.4
29	07.01.2016	0.2	0.6	0.1	5.7	0.02	8.7	9.9	5.4
30	09.01.2016	1	3	18.4	23	0.8	7.9	9.9	974
31	10.01.2016	4	10	16.1	36.5	0.44	7.1	9.5	688
32	14.01.2016	0.2	0.3	>0.1	1.6	0.03	5.8	5.9	1.6
33	21.03.2016	0.9	3	2.1	8.8	0.24	5.9	5.9	83
34	21.03.2016	0.1	0.1	>0.1	2.1	0.02	5.8	5.8	1.5

For the first monitoring period and for the 2012GF area, values are based on the comparison of a real DEM with an interpreted DEM. The sediment yield for this period and area was high, 71 +/- 28 Mg ha^{-1} yr^{-1}, reflect erosion that occurred in the 2012GF surface during the first 30 months (rilling at the swales and incision of the main channel). No erosive signs (rilling) were detected on ridges and sub-rigdes, and therefore, no interpretation of former topography was carried out for these areas. We assume that sheet erosion may have likely occurred here, and therefore, the sediment yield values may be underestimated.

Sediment yield entering the pond was not determined between September 2013 to February 2014 is included in the pond infilling. This value, 95.3 +/- 7 Mg ha^{-1} is also undeniably high. In summary, either by comparing different DEMs or by measuring sediment in the pond, calculated sediment yield values are above 70 Mg ha^{-1} yr^{-1} for the first two and a half years after construction. Our interpretation for these facts are: (i) the local base level of the reclaimed area was not accurately finished (fixed), so that the 2012GF reclaimed area underwent geomorphic adjustments, mostly in the form of decimeter incision of the main channel (and subsequent swale rilling, once the base level of the slopes, the main channel, also lowered); (ii) for unknown reasons, spontaneous revegetation (from the seeds included in the original soils that were spread on top of the geomorphic reclamation) did not occur during the first two years, unlike in an identical situation in the past and in this mine (Martín-Moreno *et al.,* 2016). Indeed, a 30% vegetation cover – one that was not attained at this time - can significantly reduce erosion of reclaimed mined areas (Moreno de las Heras *et al.*, 2009).

For the first monitoring period of the 2014GF area, the topographical comparison between a real DEM and the reconstructed one reflecting the initial surface is referred to the period of September 2014 to April 2015. For this period and area, the sediment yield was much lower, 10.2 +/- 29.9 Mg ha^{-1}, than the equivalent comparison for the 2012GF area. In this case, our interpretation is that the 2014GF area had a fixed and stable local base level from the beginning of its construction, one that was the existing pond. Revegetation at this 2014GF area was also not successful at the beginning, which indicates that the existence of a fixed base level is more important than vegetation cover.

For the second monitored period, April 2015 - July 2016, the results obtained from the direct comparison of two scans of the pond can be considered: (a) low (18.4 +/- 3 Mg ha^{-1} yr^{-1}); (b) reliable, as they are obtained from direct field measurements and for more than one year of monitoring; (c) representative of the sediment yield of the entire reclaimed area (2012GF + 2014GF). During this period of time there is evidence that during the larger runoff events, water flowed out of the pond. This water must have carried some suspended sediment. However, field evidences showed that these spilling events were rare, and we therefore assume that this circumstance does not significantly affect the obtained value.

Comparison of scanned surfaces was done for this second monitoring period and this procedure introduced uncertainty for several reasons:

(i) Among all the calculated errors, these topographies scanned in the second monitoring period in the whole area have the highest errors (almost 100%) because the changes detected are only slightly higher than the minimum detection limit. In fact, geomorphic change detection through DoDs is recommended for higher-energy systems, where the geomorphic changes are considerably larger than the minimum detection limits (Wheaton *et al.*, 2010). In our study, this condition existed for DoDs in the pond, as well as for the comparison between the reconstructed topographies and the topography scanned in 2015.

(ii) Sediment yields obtained by DoD can be affected not only by erosion/deposition, but also by shrinking/swelling effects. For example, this influence has been noticed and quantified in sub-humid badland areas (Vericat *et al.*, 2014). More than likely, the Machorro reclaimed areas will have had some shrinking, as this is a common process in reclaimed areas. This effect was neither detected nor quantified, but more than likely it occurred.

Despite the above limitations, the comparison of scans yielded similar values to those from measurements of the pond. Because the aforementioned two factors did not affect the changes detected in the pond, we therefore consider them more reliable than those obtained from comparison of scans.

The situation discussed above portraits a significant decrease in the sediment yield from the geomorphically reclaimed area after the third year, one which was not high for the 2014GF area since the beginning. This reinforces our assumption that had the local base level for the 2012GF area been firstly fixed and stable, the initial sediment yield values would have been much lower. Indeed, the trend of a decrease in erosion with time has been reported for other mining reclaimed areas in Australia (Hancock *et al.*, 2016b).

Therefore, we consider that the 18.4 +/- 3 Mg ha^{-1} yr^{-1} is the real, actual and representative sediment yield value for the geomorphically-based reclamation at El Machorro. This value is similar to those measured at this same mine for an equivalent physiographic situation (concave slope with topsoil), during 2008-2010 (from 3 to 20 Mg ha^{-1} yr^{-1}, Martín-Moreno *et al.*, 2016), even when the 18.4 +/- 3 Mg ha^{-1} yr^{-1} value represents a watershed where vegetation was poorly established at the beginning, whereas the concave slope with topsoil measured during 2008 to 2010 had a successful spontaneous revegetation from the start.

Despite the different physiographic conditions, the most comparable situation for our study (in terms of geomorphic reclamation approach and watershed scale) is with another sediment yield monitoring study carried out by GeoFluv-Natural Regrade reclamations at the La Plata mine, in the arid environments of New Mexico, United States (Bugosh & Epp, 2014). The obtained values there are 9.53 Mg ha^{-1} yr^{-1} for an undisturbed native site, 8.25 Mg ha^{-1} yr^{-1} for a GeoFluv-Natural Regrade reclamation with topdressing and poorly established vegetation and 5.65 Mg ha^{-1} yr^{-1} for a GeoFluv-Natural Regrade reclamation with topdressing and significant vegetation establishment. The values for La Plata are somewhat lower than ours. In this case, the explanation is that La Plata reclamations were properly built, without local base level variation, and also appropriately revegetated. One has to be cautious about this comparison, because the physiographic conditions differ.

Representative comparisons of our value of 18.4 +/- 3 Mg ha^{-1} yr^{-1} are also the following:

(i) it is only slightly above the one that was considered (≈12 Mg ha^{-1} yr^{-1}) of tolerable erosion rates (Wischmeier & Smith, 1978; Schmidt *et al.*, 1982);

(ii) it is in the lower part of the range 12-40 Mg ha^{-1} yr^{-1} range stablished by the Queensland Department of Mines and Energy (QDME) as a target erosion rate for rehabilitated mine sites (Welsh *et al.*, 1994; Williams, 2000).

Another interesting fact about the annual yield we derived is that it reflects a total volume of sediments transported both as bedload and as suspended sediments, because the pond was never totally filled during this lapse of time. And because the events in which water flowed out of the pond were occasional, they should not have significantly affected the obtained value.

Visual comparisons for the 2012-2016 period between the geomorphic reclamation and the dominant gradient terraces of El Machorro show that the geomorphic reclamation underwent, at most, decimeter incision of the main channel and centimeter rilling in swales, with neither rilling nor incision once base level was stable. However, terraces at El Machorro recurrently break by gullying processes, with incisions deeper than one meter in most of the cases, demonstrating that they are an unstable reclamation landform in the long term (Fig. 4.16 and 4.17).

The observed reasons for gullying of terraced constructed landforms of El Machorro are either run-on from hauling roads (Fig. 4.16) or berm failure (Fig. 4.17). The most common reason for berm failure is overtopping by sediment accumulation, due to deposition of sediment in the internal part of the berm, (Fig. 4.17). Once a berm fails it discharges concentrated flows onto the outslopes and initiates gullying.

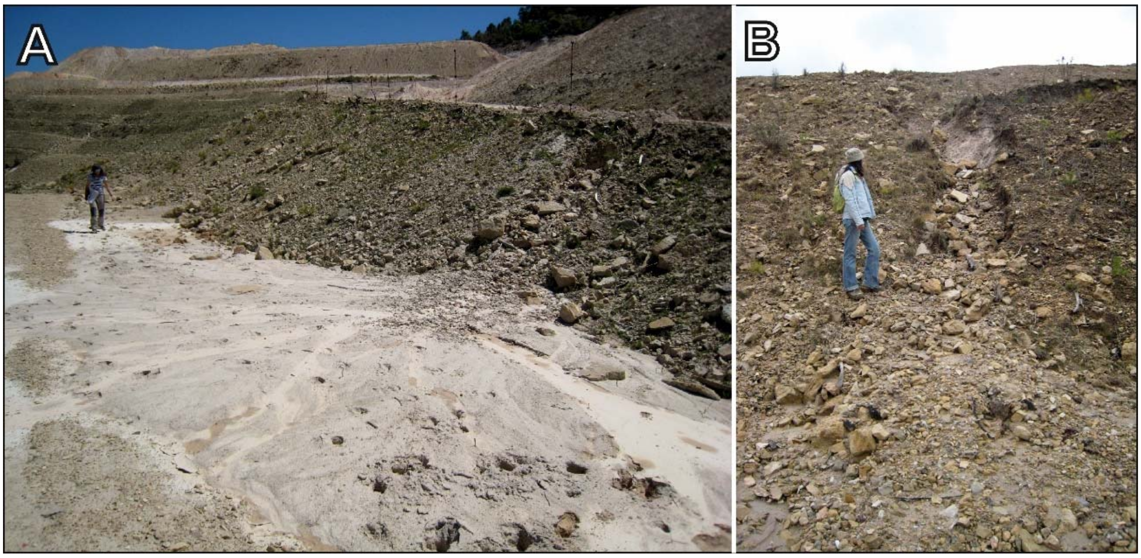

Figure 4.16. A and B: terrace reclamation landforms at El Machorro 'broken' by gullying processes due to run-on entering from internal (hauling) roads (upper left image).

Figure 4.17. Inversion of a berm slope by sediment accumulation at the toe of the upper outslope, leading to gullying downstream.

Regarding the runoff and suspended sediment monitoring, either we recorded 'false' ones or it was not possible to monitor all the runoff events. The former was caused by those situations in which the available data on runoff coefficients and on the suspended sediment fraction of the total sediment yield are inconclusive because the pressure sensor triggered the automatic sampler with 'false' events as it was covered with bedload, and/or because of freezing temperatures. Hence, it was not available for several flow events. In addition, the number of samples used to calibrate the turbidimeter was small. To avoid such a problem, water stage should be monitored by non-contact radar gauging.

Runoff coefficients range from less than 0.01 up to 0.8. The key factor appears to be antecedent rain, but the large number of missed events impeded a full understanding of the variations. Also the portion of suspended sediment yield could not be determined. Despite reporting only some of the relevant information on suspended sediment, there is a definite temporal decrease of this parameter. Events #3 and #12 delivered high loads of sediment and are associated with high values of rainfall. By comparison, although equivalent rainfall magnitudes were recorded at the end of 2015 and at the beginning of 2016 (#28, #30 and #31), they yielded much lower suspended sediment loads in 2014.

4.5. Conclusions

A holistic process around geomorphic reclamation, from designing to building to monitoring was carried out at El Machorro Mine from 2012 to 2016. A suitable and stable geomorphic analogue was found nearby, from which the corresponding inputs were measured to obtain a computer aided design of a second stream order watershed, which was thereafter properly built. This subsequently allowed monitoring its runoff, erosion and sediment yield. It is considered that the process of geomorphic reclamation, from finding suitable stable landform analogues to the monitoring process, in addition to the design and construction phases, is, in itself, a contribution, because: (a) there are not many examples of geomorphic reclamation worldwide; (b) there are very few monitoring processes of mine rehabilitation at a watershed scale; and (c) we have found only one similar situation (La Plata, New Mexico, United States) in which both conditions met.

The high sediment yield levels of the 2012GF area while base level was unstable, between 2012 and 2014, and their equivalent lower levels when it was stabilized (2014), indicate that a proper adjustment in slope and height of local base level is the most important factor of success in GeoFluv-Natural Regrade geomorphic reclamations. Once the local base level was stabilized and the reclaimed area underwent the needed adjustments, the value of 18.4 +/- 3 Mg ha^{-1} yr^{-1} is considered representative and reliable of this geomorphic reclamation because: (a) it was obtained from direct measurements of the pond; (b) it is the outcome value of a watershed, rather than from a single slope. From the latter, we stress the need for awareness that erosion values obtained from plots in mining reclaimed areas are not truly representative of what a reclaimed mined site yields as a whole.

For a more critical evaluation of the sediment yield obtained from reclaimed sites, further research is needed to evaluate its performance during a much longer period of time, compare to an equivalent behavior of terraced landforms and to the sediment yield baseline for physiographically equivalent natural areas. However, although the described geomorphic reclamation has a demonstrative character, we conclude, from its feasibility and results, that it constitutes an innovative and more sustainable solution of mining reclamation for the Alto Tajo area.

Capítulo 5

Discusión

Discusión

5.1. Limitaciones y fortalezas de las metodologías empleadas

Para la consecución de los objetivos de esta tesis ha sido necesario el empleo de un buen número de tecnologías e instrumentación asociada. En la Tabla 5.1 se puede encontrar un resumen de las mismas, así como unos apuntes sobre sus fortalezas y debilidades asociados a su aplicación en la zona minera del Alto Tajo.

En líneas generales la aplicación de las metodologías e instrumental expuestos en la Tabla 1 han permitido la consecución de los objetivos marcados en la tesis. Sin embargo, la aplicación de algunos de ellos ha sido muy problemática, debido a la combinación del contexto climático y de las condiciones particulares, y poco estudiadas desde estos objetivos, que supone una mina. A continuación, se comentan más en detalle algunos de estos problemas, los cuales habría que tener en cuenta para futuros trabajos en la zona o sitios similares:

(i) La restauración geomorfológica de la mina Machorro produjo unas altas tasas de erosión durante los primeros años tras su construcción debido a que no se consiguió fijar correctamente el nivel de base al que drenaba el conjunto de la superficie restaurada (es decir, conectar el colector principal a una altura y pendiente correspondientes a la balsa final). El motivo fue la imposibilidad de coordinar adecuadamente los trabajos de restauración con los de operación minera.

Tabla 5.1. Resumen de las principales tecnologías/instrumentos usados en esta tesis y breve análisis crítico

tecnología/ instrumento	**descripción de su uso en la tesis**	**fortalezas**	**limitaciones**
topográficos			
MS60-MultiStation (láser escáner y estación total)	la función láser escáner se ha usado en los estudios observacionales de la cárcava de Poveda y de la restauración geomorfológica para obtener topografías de alta resolución. La función de estación total ha permitido medir puntos para georreferenciar todos los trabajos topográficos y cuantificar el grado de exactitud. También, al estar integrado con la función láser escáner, el instrumento realiza la unión de los diferentes escaneos automáticamente en el instrumento, sin necesidad de tener que hacer lo posteriormente en el ordenador. Todo ello a escala milimétrica.	es el instrumento de referencia para conseguir levantamientos topográficos de alta resolución y para zonas extensas con la máxima exactitud	su aplicación en zonas con vegetación, como sucedió en el último escaneo de la zona restaurada geomorfológicamente de la mina Machorro
GPS diferencial	su principal uso ha sido para replantear los diseños de la restauración geomorfológica de la mina Machorro con precisión centimétrica. Con él se ha indicado a los maquinistas la posición de los diferentes elementos del diseño de restauración: canales, lomas y vaguadas.	permite trabajar de una forma rápida y precisa a la hora de representar un diseño CAD en campo	la falta de estaciones permanentes de referencia GNSS en el Alto Tajo hasta 2016 hizo que para su uso fuera necesario emplear su propia base de referencia, lo que dificultaba trabajos de campo
transporte de sedimentos			
turbidímetro	en la estación de medición de sólidos en suspensión situada a la salida de la restauración geomorfológica de la mina Machorro	con la correcta elección del tipo de sensor y una buena calibración, son capaces de dar valores de CSS de forma continua a cortos intervalos de tiempo	sensores como el usado aquí consumen mucha energía y en épocas de nevadas prolongadas, que afectan al panel solar que lo alimenta, puede dejar a toda la instalación sin energía
muestreador ISCO	en la estación de la mina Machorro para automáticamente recoger muestras directas de las escorrentías producidas por la superficie restaurada y poder calibrar el resto de sensores	permite conseguir muestras automáticas sin estar presentes cuando ocurren los eventos. Si la programación y el funcionamiento son adecuados, se pueden tomar muestras durante el transcurso de todo el hidrograma de un determinado evento, y durante varios eventos seguidos, sin necesidad de vaciarlos	en casos como el Machorro, donde en la mayoría de las situaciones el flujo de agua tiene poca altura y la mayoría del sedimento se mueve como carga de fondo, la parte que toma las muestras es cubierta por sedimento, impidiendo su correcto funcionamiento
muestreadores de tipo sifón	en el estudio observacional que ha permitido analizar la CSS en el arroyo Tajuelo y en el río Tajo, para obtener muestras directas de sus aguas en eventos de crecidas	permite tomar muestras de los eventos de crecida sin estar presente en campo cuando éstos ocurren, y a bajo coste	sólo recogen muestras de la parte de crecida de los eventos. A su vez, hay que vaciarlos después de cada evento

tecnología/ instrumento	**descripción de su uso en la tesis**	**fortalezas**	**limitaciones**
sensores de presión	en el estudio observacional que ha permitido analizar la CSS en el arroyo Tajuelo y en el río Tajo. También en la estación situada a la salida de la restauración de la mina Machorro, para obtener datos continuos de altura de lámina de agua. En el caso de algunos de los sensores de los ríos, el valor se transformó en caudal con datos de un velocímetro. En el caso de la estación de la mina Machorro, la transformación se realizó a partir del flume	permite registrar el caudal de forma continua y relativamente barata	funcionamiento incorrecto a bajas temperaturas o si son cubiertos por sedimento
muestreadores tipo Reid	el conjunto de sensores y demás elementos que los conforman supusieron los instrumentos centrales de la cárcava de Poveda. Su objetivo fue registrar de forma continua el flujo y la textura de la carga de fondo	única forma que existe en la actualidad de cuantificar la carga de fondo de forma precisa y continua	requiere mucho mantenimiento. Según la naturaleza del evento, los muestreadores se pueden llenar antes de que termine el evento
medidor de velocidad electromagnético de mano	se ha utilizado en el estudio observacional que ha permitido analizar la CSS en el arroyo Tajuelo para transformar los datos de altura de la lámina de agua a caudal	permite obtener datos de la velocidad del agua a diferentes alturas y secciones de forma rápida	no se puede usar en ríos muy profundos que no se pueden vadear, como el Tajo en crecidas de cierta magnitud, su uso es muy complicado, debido a la alta velocidad del agua
cuantificación del volumen de materiales almacenados en una balsa de sedimentación	se usó en el seguimiento de la superficie restaurada de la mina Machorro, para la obtención de tasas totales de producción de sedimentos	permite almacenar el sedimento emitido por una determinada superficie para un determinado intervalo de tiempo, con un mantenimiento mínimo (vaciado con maquinaria) y no se ve afectado por las condiciones, climáticas como los sensores	aunque se podría medir después de cada evento, sería costoso, de modo que sirve, sobre todo, sólo para la obtención de valores totales pierde su capacidad de medida si se llena, y requiere una limpieza inmediata, para seguir registrando
software			
LP360	para manipular las nubes de puntos obtenidas en la cárcava de Poveda y de la restauración de la mina Machorro, tanto para la limpieza y clasificación de las nubes de puntos, como para hacer cálculos volumétricos entre nubes de puntos	permite manipular ficheros de nubes de puntos de gran tamaño forma rápida, precisa y ágil en un entorno SIG	el grado de exactitud de los trabajos está totalmente condicionado al grado de conocimiento y manipulación de los numerosos parámetros del *software*
Geomorphic Change Detection (GCD)	en la cárcava de Poveda y en la restauración de la mina Machorro. Permite realizar cálculos de volúmenes y de rugosidad en topografías de alta resolución. Los cálculos se llevan a cabo sobre Modelos Digitales del Terreno derivados de nubes de puntos, en lugar de a partir de las mismas nubes de puntos	es un software libre y de uso fácil, que permite cuantificar cambios geomorfológicos ocurridos en cortos periodos de tiempo	al haber sido creado para detectar cambios geomorfológicos de una cierta magnitud, no deja introducir valores de error a escala milimétrica

tecnología/ instrumento	descripción de su uso en la tesis	fortalezas	limitaciones
metodología			
GeoFluv (implementado en el *software* Natural Regrade)	herramienta para diseñar restauraciones geomorfológicas en espacios afectados por movimientos de tierras. A nivel global se ha usado, sobre todo, en minería. En esta tesis se ha usado en la restauración de la mina Machorro	única herramienta que permite diseñar geoformas complejas, como las que componen los paisajes naturales, con una base científica y en entornos CAD	dificultad en encontrar un referente natural desarrollado sobre materiales geológicos que repliquen la naturaleza física de estériles mineros, del que sacar los parámetros para alimentar el modelo su uso requiere un manejo relativamente experto de herramientas CAD y de topografía, así como de los procesos de explotación minera, para poder hacer diseños que se adapten a la realidad
Structure from Motion (SfM)-Multi-View Stereo (MVS)	se trata de la nueva forma de denomina a la fotogrametría automática, en función de los nuevos algoritmos con los que trabaja. Permite obtener nubes de puntos de alta densidad para la elaboración de topografías de alta resolución. Se ha aplicado en la cárcava de Poveda	la obtención de las fotos es rápida y se puede hacer con casi cualquier cámara el procesado en ordenador no tiene muchos pasos y no es complicado para zonas pequeñas (escala de parcela), como ocurre en el tramo de canal estudiado en la cárcava de Poveda, ofrece resultados muy parecidos a los de un láser escáner terrestre en líneas generales, tanto la toma de fotos como el procesado es barato	el procesado en ordenador puede necesitar mucho tiempo, incluso días, según la calidad final que se quiera alcanzar se requieren ordenadores de altas prestaciones de memoria RAM para su aplicación tiende a suavizar los bordes de las gravas, por lo que puede subestimar datos de rugosidad
otros			
video cámara automática	en la cárcava de Poveda para grabar los eventos	al estar conectada a los sensores de la trampa de sedimentos, graba el total de los eventos y ha permitido explicar todos los datos recopilados por los sensores	la memoria de la cámara puede suponer una limitación. No obstante, durante su uso en esta tesis, ningún evento supero la capacidad de la tarjeta de memoria La baja calidad con la que graba por la noche. Sin embargo, esto se podría corregir con iluminación externa

tecnología/ instrumento	**descripción de su uso en la tesis**	**fortalezas**	**limitaciones**
telemetría[2]	los tres estudios de esta tesis han estado conectados por telemetría tópico	al contar con sistemas de alarmas, el procedimiento ha permitido saber cuándo se producían eventos de lluvia y la magnitud del evento que estaba ocurriendo, así como la descarga *online* de los datos de sensores	depende totalmente de la conexión de Internet. De todas maneras, todos los equipos permitían llevar a cabo una descarga directa de los datos, en caso de cortes prolongados de cobertura
Drone[2]	para la obtención de vídeos e imágenes de la evolución de la cárcava de Poveda y de la restauración de la mina Machorro	permite obtener imágenes a partir de las cuales se pueden realizar análisis cualitativos o cuantitativos (SfM-MVS) de forma rápida y barata	la baja autonomía de las baterías, por lo que para realizar un trabajo, hay que hacer varios vuelos

[2] Estos dos servicios no han sido desarrollados por mí, sino que han sido proporcionados por terceros. En el caso de la telemetría por el grupo Catch The Data y Vodafone España S.A.U. y en el uso del drone por DGDRONE (http://dgdrone.com)

A pesar de todos esos problemas, una vez fijado el nivel de base, la tasa de producción de sedimentos se redujo significativamente, confirmando una elevada estabilidad de la superficie restaurada. En alguno de los escasos estudios comparables, como la medición de sedimentos en superficies restauradas con base geomorfológica en La Plata, Nuevo Méjico, EEUU (Bugosh & Epp, 2014), donde no existieron disfunciones relativas a la conexión entre distintos niveles de base, las tasas de erosión fueron desde el principio muy bajas.

(ii) La estación de monitorización hidrológica y erosiva de sólidos en suspensión, realizada a la salida de la cuenca hidrográfica restaurada con base geomorfológica en la mina Machorro, funcionó defectuosamente. De hecho, casi la mitad de los eventos no fueron correctamente registrados, debido a un mal funcionamiento de los sensores. Esto se debió a factores como: (a) las frecuentes y prologadas temperaturas bajo cero que afectaban al sensor de presión; (b) al hecho de que tanto el sensor de presión como el filtro que toma las muestras (*strainer*) del muestreador automático fueron cubiertos por el sedimento de la carga de fondo.

En la dinámica general de transporte de sedimento desde esta zona restaurada, la carga de fondo jugó un papel más importante del inicialmente previsto. Debido precisamente a la erosión del canal principal, desencadenada por el desajuste con el nivel de base, lo que afectó el funcionamiento de los sensores. Por todo ello, este trabajo deja patente que es necesario avanzar en el uso de sensores que puedan registrar el caudal sin contacto con el flujo de agua, para que no sean sepultados por la carga de fondo. También estas estaciones podrían verse complementadas con la introducción de cámaras automáticas, como la situada en la cárcava de Poveda. La posibilidad de poder grabar todo lo que ocurre en el canal y en los sensores, durante un evento, permitiría detectar cualquier anomalía en los datos registrados, de modo que éstos podrían ser eliminados de cualquier análisis posterior, en caso de que se deban a mal funcionamiento de los sensores. O, en definitiva, podría permitir explicar el porqué de esos datos.

5.2. Transporte de sedimentos

El uso de la metodología BACI ha permitido detectar y cuantificar el efecto de la actividad minera sobre el régimen de CSS en el arroyo Tajuelo y el río Tajo. Dicha influencia cambia las CSS características de esta zona, asociadas a una cuenca hidrográfica con cubierta forestal mayoritaria, con algunos parches de agricultura, hacia otras CSS más propias de cuencas hidrográficas que incluyen un porcentaje significativo de *badlands* en su interior. Para ello, lo más importante ha sido la definición de unas líneas base *(baseline)* de CSS para los cursos fluviales del arroyo Tajuelo y del río Tajo en el entorno de su confluencia, que ofrecen datos reales (directos) a partir de los cuales se pueden establecer efectos de contaminación física debidos a la influencia de escorrentías procedentes de superficies mineras.

Con el establecimiento de esas líneas base (en plural, pues el concepto de línea base está asociado a distintas condiciones hidrológicas) de CSS, se lleva a cabo una contribución significativa, que estaba pendiente de ser realizada para este entorno, tal y como planteaba un informe inicial al respecto, encargado por el Parque Natural del Alto Tajo (Bravo *et al.*, 2004). En él se establecía que para poder realizar una correcta cuantificación del incremento de los sólidos en suspensión, desde zonas afectadas por actividades extractivas sin medidas de control, hacía falta una monitorización continua y simultánea de los ríos con y sin escorrentías de las zonas mineras.

En ese contexto, aunque existen cárcavas en el interior de estas cuencas hidrográficas, y sean una fuente natural no despreciable de sedimentos, en ningún caso pueden ser responsables del significativo incremento en la CSS aguas debajo de la zona minera. En concreto, la zona con cárcavas de la cuenca del arroyo Tajuelo, que incluye a la cárcava de Poveda, supone menos del 0.01% del total de la cuenca. En otros trabajos en los que se cuantifica la CSS en cuencas con *badlands*, y en los que se describen valores como los registrados por la estación situada en la desembocadura del Tajuelo (superiores a los 300 g l^{-1}), la superficie de cárcavas era significativamente mayor. Sirva como ejemplo la cuenca del Isábena, donde las zonas con cárcavas suponían un 0.83% de la cuenca, y cuyo efecto fue que se registró un máximo de 380 g l^{-1} (López-Tarazón *et al*. 2009).

También en la cuenca del Isábena encontraron que la variabilidad temporal de la producción de sedimentos desde las zonas de cárcavas tenía una gran influencia en la variabilidad estacional de la CSS del propio río (Buendia *et al.,* 2016). Es probable que la alta variabilidad estacional en flujo y textura de la carga de fondo que se ha detectado en la cárcava de Poveda se vea reflejada, del mismo modo que en el Isábena, en el comportamiento estacional del régimen natural de transporte de sólidos en suspensión del arroyo Tajuelo. Sin embargo, en la zona minera del Alto Tajo puede ser muy complicado conocer esta influencia natural, debido a la complejidad y gran influencia del resto de fuentes mineras.

Más allá de la implicación del aporte de sedimentos desde la cárcava de Poveda en un contexto en el que se analiza la problemática minero-ambiental de la zona, el estudio de esta cárcava ha supuesto el primer trabajo de campo de este tipo en un canal efímero, natural, de arenas y gravas. Los resultados de este estudio han evidenciado un marcado patrón estacional, en el que los aportes de arenas desde las paredes de la cárcava juegan un importante rol, tal y como apuntaban estudios previos llevados a cabo en laboratorio (Wilcock *et al.*, 2001).

5.3. La restauración geomorfológica como una solución a largo plazo ante los problemas de inestabilidad de las escombreras mineras del Alto Tajo

El efecto de las escorrentías desde zonas mineras sobre el régimen de CSS de la red fluvial del Alto Tajo ha quedado demostrado mediante la aplicación de la metodología BACI. Sin embargo, como también se reflejó, no ha sido posible determinar las fuentes precisas de esas escorrentías (lo cual hubiera requerido una investigación *ad hoc* compleja). Siguiendo este razonamiento, tal y como se señaló (Martín-Moreno, 2013) que no hay un único escenario minero, que funcione de manera homogénea, sino que hay, simplificando, dos grandes tipos: (i) minas activas con sistemas de control de la erosión y la sedimentación, que a su vez han ido adaptando las mejores prácticas de restauración a medida que han ido surgiendo, y (ii) otras inactivas que no cuentan ni con sistemas de control de la erosión y la sedimentación eficientes en las superficies que están conectadas hidrológicamente a la red fluvial del Alto Tajo, ni con restauraciones eficientes.

Como ya se ha expuesto, la ausencia de estructuras de control de la erosión y la sedimentación, o de cualquier tipo de restauración, es una anomalía técnica y administrativa, que no se ha entrado a valorar en esta tesis doctoral. En esta tesis, se parte de la base según la cual, tal y como exigen las distintas normativas ambientales y mineras aplicables en la zona, deben existir balsas para el control de la erosión y la sedimentación. En ese contexto, el rebose de esas balsas debería tener un cierto contenido en CSS (cuyo valor deberán establecer los organismos reguladores, y que podría estar basado en la línea base). Sin embargo, como también se ha comentado, tanto las restauraciones convencionales con estas estructuras para el control de la escorrentía y la sedimentación, de tipo balsa, requieren un mantenimiento indefinido. Existiendo así, la necesidad de articular otras soluciones o modelos de restauración minera en un espacio como éste, con una elevada vulnerabilidad a la erosión hídrica, que sean estables desde el corto al largo plazo. Desde el conocimiento actual sobre la temática y de los factores fisiográficos del Alto Tajo, la solución propuesta son restauraciones ecológicas mineras, basadas en restauraciones geomorfológicas. En este contexto se llevó a cabo la restauración geomorfológica demostrativa de la mina el Machorro (https://vimeo.com/110782382).

El alto grado de estabilidad alcanzado por la superficie restaurada en la mina Machorro, evidenciado tanto por los datos registrados como por lo que refleja una inspección visual de este entorno, permite afirmar, aunque siempre con las cautelas que exige confirmar esta evolución en periodos de tiempo más prolongados que la restauración geomorfológica de la mina Machorro ha sido un éxito. En este sentido, estimo que su aplicación puede constituir un modelo válido para las futuras restauraciones que se lleven a cabo en este entorno minero del Alto Tajo, teniendo en cuenta que se trata un ambiente con una elevada calidad ecológica y paisajística, y en el que el principal problema ambiental está asociado a un incremento en el transporte de sedimentos del medio fluvial, debido a la inestabilidad geomorfológica que tiene lugar en el interior de las zonas mineras. Aparte de en la mina Machorro, este modelo de restauración ha sido aplicado en otros espacios afectados por actividades extractivas de la geografía española (http://arcg.is/1JSSrD2).

No obstante, son muy pocos los estudios que aporten evidencias sobre el comportamiento de espacios en los que se ha aplicado la restauración geomorfológica. Esta tesis constituye uno de los escasos estudios que ha realizado un proceso de monitoreo de un periodo de varios años sobre superficies restauradas geomorfológicamente añadiéndose a antecedentes (p.ej., Bugosh & Epp, 2014) a escala de cuenca, o en una ladera cóncava (Martín-Duque *et al*., 2010). En esta línea hay que seguir avanzando en la investigación de este tipo de restauraciones, aumentando el número tanto de ejemplos demostrativos como de superficie de cada ejemplo, e instalando equipos más adecuados para su monitorización en este tipo de condiciones climáticas y orográficas, tal y como se ha señalado anteriormente. También sería interesante poder mantener el estudio sobre la estabilidad de estas superficies en el largo plazo, de modo que las conclusiones obtenidas sean más representativas.

5.4. Modelo de restauración y de manejo de escorrentías y sedimentos propuesto para las explotaciones de la zona minera del Alto Tajo

Sobre la base de todas las investigaciones llevadas a cabo desde 2007, y sobre todo por las más recientes que componen esta tesis, se propone el siguiente modelo de explotación-restauración para las dos minas activas de la zona, Machorro y María José (Fig. 5.1):

(i) Ambas minas muestran unas escombreras 'exteriores' construidas siguiendo el modelo berma-talud, a modo de gran pantalla visual, en cuyo interior quedan los huecos de explotación activos y los frentes. Este modelo berma-talud de las restauraciones ya existentes (a), se aplicó en su momento dado que constituía la mejor práctica disponible, y dadas sus dimensiones actuales, carece de sentido plantear cualquier remodelado del terreno, dado que implicaría un movimiento de tierras extraordinario. Estas escombreras han sido, en general, bastante estables hasta la fecha; sin embargo, como ya se ha comentado anteriormente, presentan dudas sobre su estabilidad a largo plazo, ya que de manera esporádica, pero recurrente, se producen roturas de todo el sistema en terrazas por erosión en cárcavas, que afecta a varios escalones.

Para estas zonas se recomienda seguir un manejo similar al que existe actualmente, garantizando un mantenimiento de las bermas, dado que las escorrentías que circulan por éstas, están finalmente conectadas al sistema de balsas, con mantenimiento, de la mina. Al mismo tiempo, habría que monitorizar la evolución de las cárcavas-regueros que van apareciendo, para conocer si tienden hacia su estabilización o aumenta su actividad erosiva.

Figura 5.1. Representación, sobre una vista oblicua de la mina María José, del modelo de restauración y de manejo de escorrentías y sedimentos propuesto para las minas activas del Alto Tajo. Ver texto para su explicación. Foto: Paisajes Españoles.

(ii) En las zonas interiores de las minas, con morfología de "valle" (entre el frente y las escombreras exteriores), donde la actividad extractiva vaya cesando (b1), se propone ir introduciendo restauraciones ecológicas con base geomorfológica, para lograr una estabilidad dinámica *(steady state)* del terreno, tal y como parece haberse logrado en la cuenca restaurada de la mina Machorro. La tasa de producción de sedimentos actual de esta superficie avala esta afirmación. No obstante, como ya se ha señalado, hay que seguir estudiando su evolución en el largo plazo, para confirmar o no este hecho. Para ello, se propone introducir, en la actual estación de la mina Machorro, las mejoras que se han comentado en el primer punto de la discusión. También sería recomendable el estudio de la dinámica de carga de fondo usando muestreadores de tipo Reid, como los usados en la cárcava de Poveda.

(iii) En las zonas activas (b2), con independencia de la restauración progresiva, que se propone que sea ecológica con base geomorfológica, habría que seguir manejando las aguas y sedimentos, tal y como se viene realizando, mediante sistemas de balsas para el control de la escorrentía y la sedimentación, interconectadas y garantizando su mantenimiento (limpieza).

(iv) Para los frentes de explotación (b3) se propone también un remodelado geomorfológico que garantice su estabilidad, replicando formas erosivas estables. Los detalles de este modelo quedan fuera de los objetivos de esta tesis (Balaguer *et al.*, 2014). En todo caso, esta recomendación, que es más aplicable a yacimientos homogéneos, es más complicada en las explotaciones de caolín estudiadas, debido a que el avance extractivo se basa en la selección necesaria de minerales procedentes de distintos sectores (bloques y niveles) de los frentes mineros que presentan una elevada heterogeneidad (vertical y lateral) de calidades, todo ello con vistas a obtener un mix uniforme de mineral todouno suministrado a planta de tratamiento. (Lázaro Sánchez, com. Pers.)

(v) En la zona de conexión entre la balsa final y la red fluvial (c), control de las escorrentías esporádicas de rebose del dique final de esa balsa, usando como referencia de calidad, como articule quien proceda (reguladores) los datos de nivel de base de CSS definidos para el arroyo Tajuelo. Desembocadura de las escorrentías de la mina (c): En cada punto final de desembocadura de los sistemas de balsas de las minas hacia la red fluvial (pues puede haber más de uno), debería existir una estación automática de CSS, para asegurar que se conoce ese parámetro, y que éste cumple con las normativas que proceda, para las cuales proponemos considerar la información de la línea base establecida para el arroyo Tajuelo.

(vi) Utilizar el conocimiento adquirido en el estudio sobre el transporte de sedimentos como carga de fondo para desarrollar futuras investigaciones sobre el movimiento de arenas y gravas tanto en el interior de las minas como en la red fluvial del Alto Tajo afectada por sedimentación.

Capítulo 6

Conclusions

Conclusions

The following conclusions are based on the studies developed at the mining area of the Alto Tajo Natural park:

1. The very active ephemeral Poveda gully has a seasonal pattern in bedload transport and morpho-texturel. The channel fills in spring and winter with sand, having a low relative relief, but incises a narrow, coarse-grained thalweg in autumn. Spring and winter events contribute considerable sand that covers the gravel, fills the incised thalweg, and causes the channel to become fine grained, most of it sandy.

2. The high seasonal and event variability of bedload transport and channel shape in the Poveda gully derive as a result of sand supply from the walls and bar formation and obliteration.

3. Gravel motion is considerably dependent on the presence of sand in the Poveda gully channel. Without sand, gravel remains immobile in all but very large flow events.

4. The BACI approach is a simple and reliable method to determine mining, or other human impacts on SSC. Thus, based on the BACI approach developed in this area, there is a mining effect over the suspended sediment concentration (SSC) in the Tajuelo and Tajo waterways. This effect changes the typical SSC dynamics of a forested catchment with abandoned agriculture toward another regime, similar to one of a catchment with *badlands*. Other sediment sources, such as gullies (including the Poveda gully), are not responsible of the Tajuelo's SSC increase. Specifically, the highest detected SSC upstream of the Tajuelo

mines was 24 g l^{-1} whereas the highest simultaneous downstream value was 391 g l^{-1}, more than one order of magnitude higher than the supposed baseline (the referred 24 g l^{-1}). Additionally, this value is 1000 times higher than the average concentration of 25 mg l^{-1}, used by the European Union until 2015, to guarantee the quality of salmonid waters.

5. Indeed, this research demonstrates that the all-European 25 mg l^{-1} upper value for SSC, is not a reliable criterion to quantify SSC impacts. Although the law promoting that value suggested that it could be derogated “because of exceptional weather or special geographical conditions”, and also because “floods are liable to cause particularly high concentrations”, it does not contain information how to establish a proper baseline. Therefore, it entails a narrow interpretation and use of the 25 mg l^{-1} value is not to be continued.

6. An SSC baseline has been defined for the mining area of the Alto Tajo Natural Park with reference to the Tajuelo stream and for the Tajo river.

6. The El Machorro geomorphic reclamation and its subsequent monitoring are significant advances in the application of a Geomorphic Reclamation approach in mined sites, because: a) there are few examples of mining geomorphic reclamations worldwide; (b) there are very few monitoring processes of mine rehabilitation examples, both with conventional and with geomorphic approaches, and even less at a watershed scale.

7. The sediment yield of the geomorphically reclaimed area is presently 18.4 +/- 3 Mg ha^{-1} $year^{-1}$. This value is in the lower part of the 12-40 Mg ha^{-1} $year^{-1}$range established by some regional Australian authorities for mining restoration.

Therefore, it can be concluded that El Machorro geomorphic reclamation has been successful.

8. Further research is needed to determine the long-term stability with respect to the present sediment yield by: (a) evaluating its performance in a much longer period of time, and compared with an equivalent behavior of terraced landforms; (b) comparing it with the sediment yield baseline for equivalent physiographic situations.

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Lista de acrónimos

Español

CSS (Concentración de Sólidos en Suspensión)

PNAT (Parque Natural del Alto Tajo)

English

ASPRS (American Society for Photogrammetry and Remote Sensing)

ATNP (Alto Tajo Natural Park)

BACI (Before-After Control-Impact)

CAD (Computer Aided Design)

DEM (Digital Elevation Model)

DoD (DEM of Difference)

GCD (Geomorphic Change Detection)

GSD (Grain Size Distribution)

HRT (High Resolution Topographies)

LEM (Landscape Evolution Models)

$_{min}$LoD (minimum Level of Detection)

MVS (Multi-View Stereo)

RMSE (Root Mean Square Error)

RMSH (Root Mean Square Height)

RMSEZ (Root Mean Square Error in height)

SfM (Structure from Motion)

SSC (Suspended Sediment Concentration)

SSL (Suspended Sediment Load)

TLS (Terrestrial Laser Scanner)

TS (Total Station)

Q (discharge)

QDME (Queensland Department of Mines and Energy)

WQG (Water Quality Guidelines)

Anexos

Anexo 3 (Appendix 3): Summary and analysis of the main technologies and instruments used during the thesis

technologies/instruments	description of its application in the thesis	strengths	limitations
topography			
MS60-MultiStation (Terrestrial Laser Scan, TLS,) and Total Station, TS)	TLS capability has been used at the Poveda gully and Machorro reclamation to get high resolution topographies. Total station capability has been also used in both studies to measure points to calculate accuracy and to georeference topographies. Because TS is integrated with TLS in a single instrument, it has been also used to automatically unify the different scans of each survey within the instrument, without being necessary to spend time in registration process in the computer	it remains being the best instrument to get high resolution topographies for large areas with the maximum accuracy	its use in areas with vegetation, such as in the last scan of the reclaimed area in El Machorro
differential GPS	its main use has been to stake out the El Machorro geomorphic reclamation designs at the field with a centimetric precision, allowing showing the operators the reference points from which the different landforms of the design could be built: channels, sub-channels (swales), ridges and subridges (rounded hills)	It allows working, in a flexible, quick and unequivocal way, to deploy the CAD designs at the field	because of the absence of permanent GNSS stations in the Alto Tajo Natural Park until 2016, it was needed to use GPS with its own base station, which made difficult to work in the field
sediment transport			
turbidimeter	used in the SSC station at the mouth of El Machorro reclamation	with a suitable sensor range and calibration, it can measure SSC accurately and continuously at short time spans	sensors as used in Machorro reclamation (with high range) consume much energy, so that during long snowfall periods, they can end up all the energy supplied by the solar panel, stopping even the whole station
ISCO sampler	used in the SSC station at the mouth of El Machorro reclamation, to automatically take samples of the runoff from the whole catchment and to calibrate the sensors	with the proper programming, it can take samples from a whole event (rising and recession limb, as well as base flow), and during consecutive events, without the need of being in the field	in El Machorro station, it did not work adequately because the strainer was often covered with bedload, preventing it from taking samples. This is partially conditioned by the kind of runoff produced here: short water height with high sediment concentration

technologies/instruments	description of its application in the thesis	strengths	limitations
siphon samplers	It has been used to define the SSC in the Tajuelo and Tajo rivers in the rising limb of the events	they take samples form the rising limb of the events without being in the field. They are also cheap	they do not take samples from the recession limb of the events. They need to be emptied before the next event will occur
pressure sensor	to measure water height, to understand SSC in the Tajuelo and Tajo rivers. Used also in El Machorro reclamation, with the same purpose. Pressure values were transformed to discharge with velocity data for the rivers and with the flume for El Machorro station	they continuously measure discharge in a cheap way	wrong operation below zero degree temperatures and when they are covered by sediment
Reid-type slot samplers	all together sensors and devices were installed in the Poveda gully to record bedload flux and texture	the only way to quantify bedload transport from an accurate and continuous way nowadays	they need considerable maintenance. Depending on the event, they can be totally filled with sediment before the event ends
electromagnetic current meter	to measure flow velocity in the Tajuelo (SSC study), so that water heights recorded from pressure sensors can be converted into discharge	allow getting water velocities at different water heights fast	it cannot be used in deep waters, such as in the Tajo it can not be used during some flood events because of the high velocity of the flow
sediment volume quantification retained by a pond	used in El Machorro reclamation monitoring to calculate sediment yields	the pond kept almost all the sediment produced by the reclaimed area with a minimum maintenance. It is not affected by extreme climatology factors, as it happened with sensors	It is expensive to make measurements after each event, to know yields at event scale it does not store sediment yield if it is full, and also, even if not full, some spill can occur, so that both maintenance and spill controls are needed
software			
LP360	used to clean and classify point clouds derived from the Poveda gully and El Machorro reclamation. Volumetric analyses have been done as well	it allows working with heavy point clouds from an easy, fast and accurate way in GIS environments	getting successful results depends on an expert knowledge of the different software tools and parameters

technologies/instruments	description of its application in the thesis	strengths	limitations
Geomorphic Change Detection (GCD)	used in the Poveda gully and El Machorro reclamation. It allows calculating volumes and roughness by using high resolution topographies. Quantifications are made from Digital Elevation Models derived from point clouds	it is free and can be easily used to calculate geomorphic changes	it does not allow introducing accuracy values in millimeter units to derive error surfaces. The minimum is 1 cm. It seems to be a computational mistake
methodology			
GeoFluv (implemented at the Natural Regrade software)	tool to make geomorphic landform design, for reclamation, in areas affected by earth movements. Widely used in mining areas worldwide and here it has been used in El Machorro geomorphic-based reclamation	the only available tool to design complex natural landforms, based on geomorphic scientific basis, in CAD platforms	finding a suitable geomorphic referent is a demanding task. It needs to have the same geology properties (materials and slope) as the geomorphic restoration that it is going to be done, to feed the model its use needs an expert knowledge of CAD, topography, as well as mining operations, in order to produce realistic outcomes
Structure from Motion (SfM)- Multi-View Stereo (MVS)	the new way to call automatic photogrammetry considering its algorithms it allowed getting dense point clouds to obtain high resolution topographies in the Poveda gully	almost each camera can be used to get photos and the process of getting the pictures is fast the workflow in the computer does not have many steps and they are not complex for small areas (referred as plot scale in the literature), as Poveda gully, it surveys topographies similar to TLS in general, the whole process (taking pictures and processing them in the computer) is cheap	computer workflow can take several hours or even days, depending on the wished quality it requires powerful hardware, overall high RAM memory it tends to smooth gravel shape. So, it can underrate roughness values
others			

technologies/instruments	description of its application in the thesis	strengths	limitations
video camera recording	event video recordings in Poveda gully	it can be triggered by the sensors of the trap being able to record the whole event. It has been key to explain the data recorded by the sensors during the events	camera memory can be full until the event finished. Nevertheless, this has not happened in this experiment the low quality at night. It can be solved by introducing additional illumination
telemetry[3]	all the instruments have been connected by telemetry, letting me to check and download the data without being in the field	the alarm system allowed knowing the initiation of any rain event and its magnitude at the end. In addition, I was able to download the data from the sensors online	totally dependent of Internet connection. In any case, each sensor allowed downloading the data directly by using a cable and computer, if there were long periods without Internet connection
Drone[3]	it has been used to record videos and take images from the Poveda gully and El Machorro reclamation	getting images to make qualitative and/or quantitative (SfM-MVS) analyses, quickly and cheaply	low autonomy of the batteries. Hence, to complete a full job, it is necessary to make several flights

[3] Those services have been provided by Catch The Data and Vodafone Spain S.A.U. (telemetry) and DGDRONE (http://dgdrone.com) (drone).

Anexo 4: Enlaces a recursos digitales disponibles Internet

- **Vídeo restauración geomorfológica Machorro**:

https://vimeo.com/110782382

- **Vídeo estabilización escombrera Nuria** donde se puede ver la aplicación de *GeoFuv-Natural Regrade*, GPS diferencial, Multiesación y drone en otro proyecto del Alto Tajo: https://www.youtube.com/watch?v=rYDQoGGd4l0

- **Vídeo seguimiento topográfico cantera de Somolinos** donde se puede ver el uso de *SfM-MVS* (fotogrametría moderna) aplicado a escala de cuenca: https://www.youtube.com/watch?v=cLXiXzVvoXc

- **Web Restauración Geomorfológica**: www.restauraciongeomorfologica.es

- ***STORY MAP* resumen de todas las restauraciones geomorfológicas llevada a cabo por Restauración Geomorfológica en España**: http://arcg.is/1JSSrD2

- ***Web map* de las investigaciones llevadas a cabo por el grupo en la zona minera del Alto Tajo en los últimos años**:

http://ucmadrid.maps.arcgis.com/apps/OnePane/basicviewer/index.html?&extent=%7b%22xmin%22:-247255.39541376586,%22ymin%22:4940879.718515975,%22xmax%22:-193061.5423596489,%22ymax%22:4980779.847280784,%22spatialReference%22:%7b%22wkid%22:102100%7d%7d&appid=ba36862ff58742c4a700d9222d3a53e9

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